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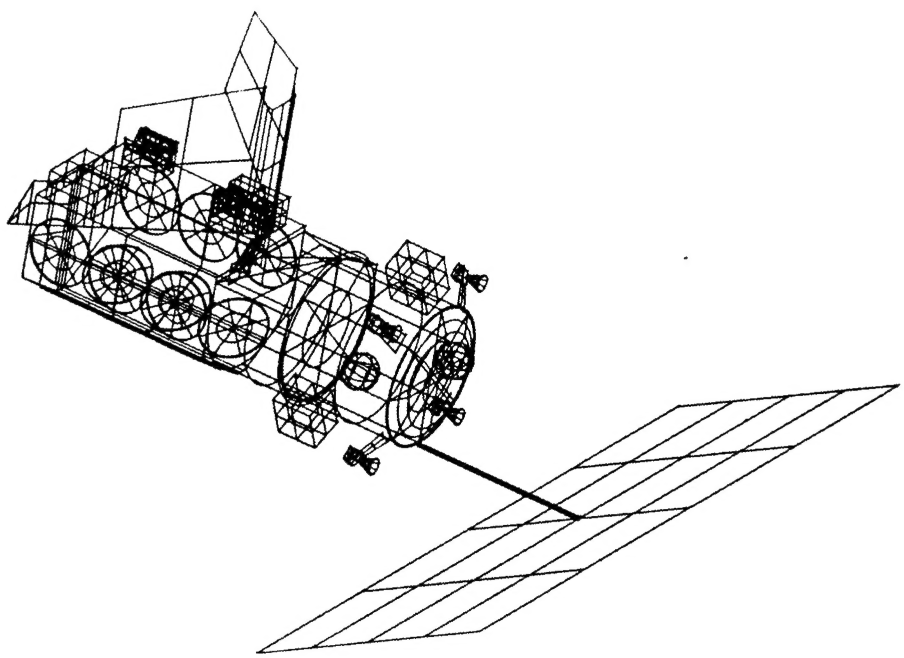
Independent Research and Development

SUMMARY REPORT

April 1999



THE AEROSPACE CORPORATION

To provide architect-engineering support to national security space missions, Aerospace must be at the scientific and technological forefront of those missions. Aerospace Independent Research and Development therefore concentrates on problems of long-range importance and potentially high payoff in future space system architectures.

Edward C. Aldridge, Jr.
President
The Aerospace Corporation

Foreword

This report presents selected summaries of the results and progress achieved by the Aerospace Independent Research and Development program during the period from 1 October 1997 through 30 September 1998. More detailed accounts are given in Aerospace Technical Reports (ATRs), published as particular milestones are reached, as well as in journal publications.

Management responsibility for the program is assigned to the Group Vice President, Engineering and Technology. He is supported by the Research and Program Development staff, who are responsible for reviewing, evaluating, and recommending projects for funding, as well as for periodic reviews of ongoing projects.

J. R. Parsons
Group Vice President
Engineering and Technology

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Introduction

The Aerospace Corporation provides architect-engineer services for military space and launch systems, and for other projects related to national security. Aerospace's work is primarily under contract to the Space and Missile Systems Center of the Air Force Materiel Command, providing support in the planning, design, development and operations of complex space systems. To carry out this mission, it is necessary for the Corporation to engage in a vigorous and continuing research and development program.

Aerospace's research and development efforts advance critical technologies needed for present and future military space systems. They contribute directly to Aerospace's missions: conceptual design, systems engineering, launch readiness verification, on-orbit diagnostics, and anomaly analysis; and to the assessment of mission performance and cost and schedule risks.

The structure and mission of The Aerospace Corporation's research and development program is coordinated with, and complementary to, that of the Air Force Research Laboratory and other organizations actively working in space system-related technology.

As part of its overall research program, the Corporation engages in an Independent Research and Development (IR&D) program, consisting primarily, but not exclusively, of long-term research. Many individual projects constitute the IR&D program. The objectives of the program are to:

- Develop analytical tools, technical facilities, and scientific and engineering state-of-the-art expertise essential to the solution of critical space system problems in an objective, timely, and cost-effective manner
- Provide the basis for Aerospace to take a technical leadership role in interactions with the government and contractor communities
- Provide scientific and engineering advances and methodologies that will be important in planning and developing advanced space, launch, and ground systems or improvements to existing systems
- Allow efforts in research and technology to build corporate capabilities in multi-use applications
- Maintain a dynamic link with academic, government, and industrial technical communities to stay abreast of new developments that may influence new concepts and applications of space and launch systems
- Attract, develop and retain a high-quality professional staff

In line with these objectives, broad guidelines for the direction and emphasis of the research and development activities at Aerospace are periodically developed to assess in detail the trends in relevant technologies and their application to military space systems. Research and development activities are presently conducted in seven broad areas:

- Spacecraft and Launch Vehicles
- Electronic Device Technology
- Communications and Navigation Technology
- Information Sciences
- Environmental Technology
- Surveillance Technology
- Systems Engineering

Four Corporate Research Initiatives that utilize the multidisciplinary capabilities of several laboratory and engineering centers have been identified as particularly timely innovations affecting all of the nation's commercial and military space programs:

- Aerospace Hyperspectral Imager
- Commercial Microelectronics for Space
- Microtechnology for Space Systems
- Reusable Launch Capability Development

Two Corporate Strategic Initiatives address future systems areas in which Aerospace must establish a firm base of analytical and systems design expertise in order to contribute effectively to the evolution of new space systems and architectures:

- Space Debris and Reentry Breakup Research and Development
- MicroElectroMechanical Systems (MEMS)

Because the IR&D program is of great importance to the long-term objectives of the Corporation, and because it uses a substantial fraction of corporate overhead, the program is reviewed annually by the Technical Committee of the Board of Trustees, and their recommendation is acted upon by the full Board. Since the inception of the Corporation, the Board of Trustees has vigorously supported the research program and allocated to it a substantial share of corporate resources.

This IR&D Summary Report for FY 1998 contains brief reports of selected projects carried out under the program. They are a representative sample of the wide range of Aerospace internal research interests, from basic science to operational space systems engineering. This report also includes abstracts of all projects undertaken in FY 1998, and a bibliography of recent IR&D publications. For further details on any of the individual projects, please contact the authors.

Corporate Research Initiatives

Microtechnology for Space Systems

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Microtechnology (the confluence of microelectronics, microelectromechanical systems (MEMS) and advanced packaging to create unique microinstruments) continues to be one of the most rapidly expanding technology areas. The Aerospace Corporation, recognizing the benefits of this technology since 1990, has focused on maintaining a leadership role within the space MEMS community to accelerate the insertion and application of small, low-cost, reliable subminiature devices into military space systems. This has been accomplished through leveraging of terrestrial MEMS development efforts as well as the establishment of our own microtechnology Corporate Research Initiative (CRI). The CRI, now in its third year, comprises four elements:

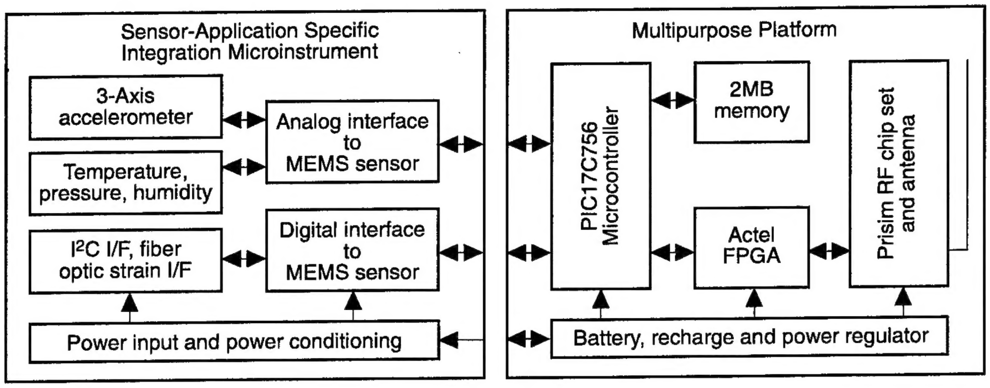
- Task 1: Develop an Application-Specific Integrated Microinstrument (ASIM) wireless multiparameter sensor
- Task 2: Demonstrate a flight qualifiable MEMS-based Guidance, Navigation and Control (GN&C) system
- Task 3: Develop micropropulsion technology
- Task 4: Develop a space system design methodology appropriate for nanosatellites.

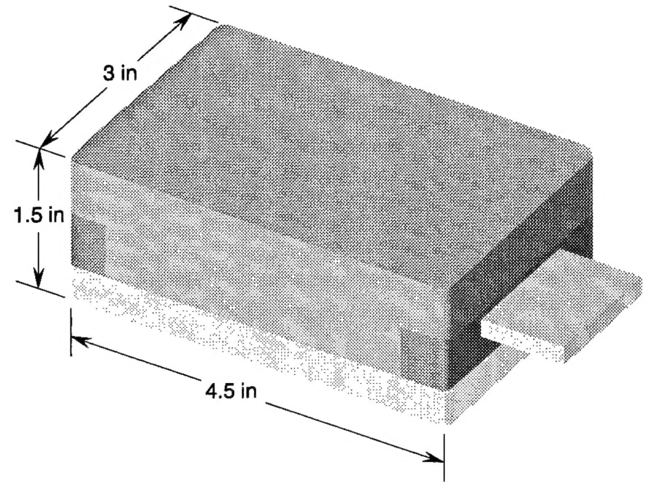
Progress in each task is summarized below.

A MEMS wireless multiparameter sensor (MPS) is a combination of multiple microelectromechanical sensors measuring several environmental parameters integrated together with local computing, data storage, wireless communication and power. The MPS is organized in a network so that hundreds of such nodes may communicate to a centralized data archiving computer. In FY98 the primary goals of Task 1 were the development of a networked, wireless, MPS technology demonstration system and the development of a palm-sized MPS, using 3-axis MEMS accelerometers, pressure, humidity and temperature sensors. In addition, efforts were made to develop novel MEMS sensors specialized for launch operations and to demonstrate MPS relevance to Air Force needs.

MPS electronic system development emphasized two major efforts. First, we have developed a technology demonstrator for our MPS concepts using commercial-off-the-shelf (COTS) technology that emulates the functionality of our proposed palm-sized MPS. By using a custom sensor board and laptop computer communicating wirelessly to a master node, implemented using another laptop computer, we have demonstrated MPS functionality. This functional equivalent technology demonstrator allowed us to evaluate various sensor configurations, to experiment with wireless network protocols, and to demonstrate MPS capability to potential new business customers. Secondly, we have developed major portions of our palm-sized MPS sensor. We have completed board level designs and fabricated two electronic breadboards. These breadboards were used to evaluate sensor performance, test microcontroller operation, and develop MPS software codes. Our sensor breadboard (Figure 1) has been tested in the laboratory and provides a multiparameter measurement of 3-axis acceleration (±50G each), temperature (−25°C to +105°C), pressure (0 to 16 PSI), and humidity (0 to 100%). Although commercial sensors are currently used to achieve optimum versatility with reduced development cost, we have allowed for the use of custom in-house developed sensors. An additional sensor needed for the MPS is an ultra-low-power acoustic shock wake-up sensor. We have designed and fabricated such a sensor using MEMS techniques and we are currently developing the electronics to evaluate its performance. Additionally, we have designed, fabricated, and tested a compact battery pack with power regulation to provide operating voltages to the MPS during extended unattended operations. Lastly, to enclose our sensor electronics, we have designed and fabricated

Figure 1. MPS internal electronic block diagram and MPS sensor package. The palm-sized MPS sensor currently measures temperature, pressure, humidity and 3-axis acceleration, communicating this information wirelessly to a base station computer up to 1000 ft. away. The MPS has been designed with a flexible sensor interface to accommodate Aerospace-developed fiberoptic and chemical sensors.





palm-sized mechanical hardware and begun to test this hardware for mechanical robustness.

Software efforts this year have focused on the codes for the MPS sensor node. Based on operating requirements, software modules addressing individual tasks were designed. The modules were defined, developed and tested using commercial development tools. The modules were then used to validate portions of the hardware design. The modules were programmed primarily using the C programming language to maximize portability to other systems. Nearly all software modules have been designed and written and are currently being tested on our breadboards to allow for co-development of hardware and software. The modules have demonstrated acquisition of data upon receipt of a hardware trigger and transmission of data to a master node using a serial communication protocol.

Significant progress in the development of a MEMS chemical microsensor for hydrogen chloride (*HCl*), based on phthalocyanine coatings, has also been made. Magnesium phthalocyanine was identified as a good candidate and methods were developed to purify, deposit, and characterize it as a sensor coating. We made an important discovery about this material; the stable form at room temperature contains two waters of hydration. This has a dramatic effect on the conductivity of the sensor and has important implications for its use as a chemical sensor. We also have made good progress in the development of a MEMS micro hot plate sensor array. The *HCl* microsensor functions via a phthalocyanine coating on a small, suspended, thermally-isolated substrate (hot plate) heated to 150°C. Figure 2 shows a photograph of a micromachined hot plate array (16 separate microsensors (~400 μm each) all on a 2.5 mm die) designed at Aerospace and fabricated using an outside silicon foundry (MUMPS) and in-house post-processing. A promising method for post-processing the die to create thermally-isolated structures was developed that involves a combination of chemical and laser etching techniques. At the end of this year we demonstrated a functioning device using this method, and next year the chemical sensor coatings will be integrated onto the array.

To demonstrate the direct relevance of our technology to Air Force space program needs, we have targeted the MPS as a means to monitor the impact magnitude, impact location, handling vibrations, temperature, and humidity environments experienced by the Delta launch vehicle graphite-epoxy motor casings. This year we used the MPS technology demonstrator and integrated it with a separate fiberoptic strain measurement system to measure impacts on a 0.5m by 1m section of the casing. Invention disclosures relating to this effort have been submitted.

The objective of Task 2 is to fabricate a space-qualifiable navigation and vehicle attitude sensor suite by fusing measurements from MEMS gyros and accelerometers, a GPS receiver, and a magnetometer. Strapdown equations of motion are integrated using gyro and accelerometer measurements to form a navigation solution. The relatively high drift and noise characteristics of the MEMS instruments suggest they may not be suitable, when used alone, for some guidance and control or range safety tasks. A sensor fusion approach using an extended Kalman filter with redundant data from a GPS receiver and yaw-sensing magnetometer provides higher quality navigation and attitude information.

This year's effort focused on development of a GPS receiver and IMU testbed using an industry-standard VME bus (Versa Module Europa) from VME Microsystems International Corp. The choice of a VME bus

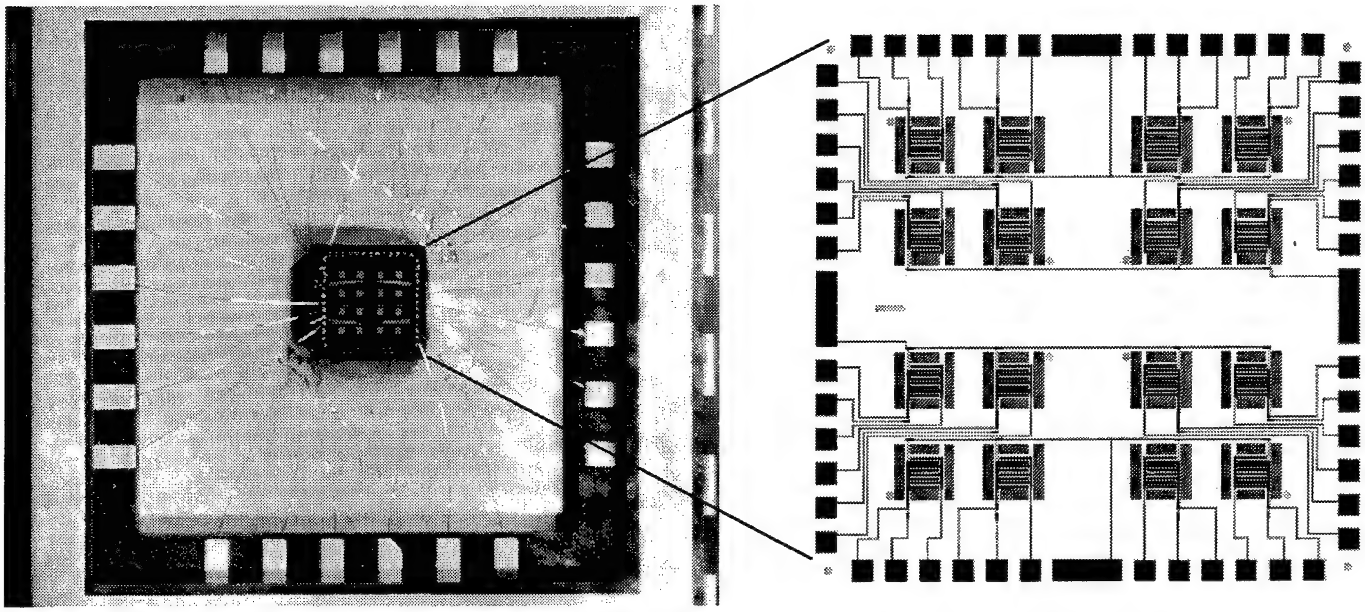


Figure 2. Micro Hot Plate Sensor Array prototype fabricated at Aerospace using the MUMPS foundry service. This is an array of 16 sensor elements micromachined in silicon and mounted in a standard 24-pin chip carrier (left). On the right a schematic of the chemical microsensor array is shown. In this prototype, the silicon behind the center four elements has been etched away and electrical contacts have been established with six heaters and electrode sets. Temperature measurements were made with IR thermography.

emphasizes low development risk at the expense of an increased physical size of the unit; it is a tried and tested system for real mission flight hardware and software.

The navigation correction algorithm, an extended Kalman filter, was upgraded to a tightly coupled approach to provide estimates of vehicle position, velocity, and GPS receiver clock bias along with attitude corrections and IMU biases. In a tightly-coupled filter, satellite range data are used directly rather than being preprocessed by the GPS receiver. Integrating a magnetometer yaw-sensing instrument demonstrated flexibility of the hardware, software, and navigation algorithm. Yaw measurements improve observability of the heading and three of the IMU bias estimates.

Testing was conducted in three phases. The first phase involved testing the software and fusion algorithm only. A flight simulator was developed to generate IMU outputs for an assumed flight profile. GPS data were synthesized from observations made by a stationary receiver and adjustments made to allow for the simulated trajectory. Performance was evaluated by comparing the computed flight profile against truth as given by the simulation. Position estimation errors were within the limits imposed by GPS selective availability; roll and pitch estimation errors were less than one degree. Phase 2 involved testing all the hardware and software in a realistic environment of acceleration, turns, satellite dropouts, shock and vibration. The integrated GPS/MEMS IMU system was mounted in a van and driven over 20 miles on local freeways. Figure 3 shows the navigation solution superimposed on a map of the route taken. A detailed analysis of relative contributions from the MEMS IMU and GPS to the overall system performance is to be done, in particular with regard to the apparent navigation anomaly in the norhtwest corner. Figure 3 clearly indicates a respectable navigation solution with apparent errors within the GPS selective availability bounds (50 meters) and overall health of the hardware and software integration.

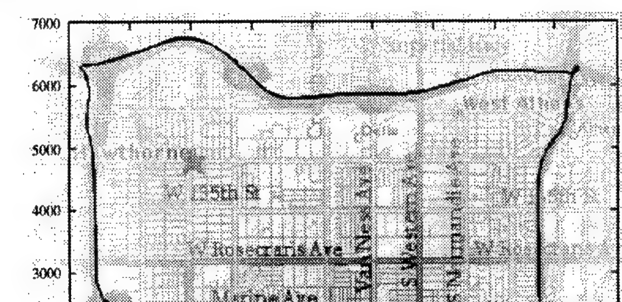


Figure 3. Road test indicates overall health of the hardware and software integration for a MEMS navigation system.

Preparations for evaluating the system in a flight test are almost complete. All necessary hardware has been acquired and assembled and a Twin-Otter aircraft is available. A flight test, however, has been postponed until next year because of insufficient funds.

The performance of MEMS/MEMS-like gyros from Boeing North American, Systron Donner, and Murata was also evaluated through bias and scale-factor testing. As expected, their performance as a function of measured bias stability is not adequate for most of the standalone inertial navigation or closed-loop control applications.

The Task 3 goal is to develop and test batch-fabricated micropropulsion concepts for future nanosatellites and microsatellites. In particular, we are constructing micro cold gas, resistojet, and ion engines that can produce micro-to-milli-Newton thrust levels. Our recent accomplishments can be split into two broad categories; microfabrication development and thruster or component development.

During the past year, the laser-machining facility produced components for microfabrication development and for the DARPA-supported "Digital Micropropulsion" effort performed jointly with TRW and the California Institute of Technology. Rapid fabrication of multiple components on a single wafer was enabled by the development of step-and-repeat software for the laser machining station, design and fabrication of a new 4-inch wafer holding stage to ensure surface flatness and orthogonality with the laser beam, and development and fabrication of an improved wafer etching system. Figure 4 shows an example of what can now be fabricated within one working day across a 4-inch wafer; an array of Aerospace logos in a photosensitive glass called Foturan [1]. The "cuts" are 30 microns wide by 300 microns deep and the circles are 800 microns in diameter.

Micropatterned Foturan glass can be converted into a tough ceramic by baking. The ceramic form is stronger than aluminum, can be cycled over a wide temperature range (>800°C), and yet maintains a high dielectric constant. During this year, we explored how the programmed temperature profile for ceramization affects grain size and feature resolution imprinted on the microstructures. By tailoring the temperature profile in a critical region of the program cycle, we could generate variations in surface texture at the micron-scale.

We also investigated thermal fusing of aligned Foturan glass layers and the deposition of metal and conducting lines at specific sites. Our preliminary data show that very good bonding can occur as low as 200°C, but wide variations exist. We are now improving process control by quantifying the force applied, the surface finish, and surface chemistry to reduce the observed variations. We are also developing a direct-write conductor patterning technique whereby a laser beam "seeds" a surface with an appropriate metal and width profile. This surface pattern "seeding" step can be done very quickly since very little metal (a layer nanometers thick) is deposited at any one location. We used a 248-nm laser to "write" roughly 50-micron wide lines of palladium "seed" onto glass in a room-temperature bath of dilute aqueous palladium chloride. The glass was then immersed in a second electroless nickel bath to add bulk and increase conductivity. We plan on further developing this promising microfabrication process next year.

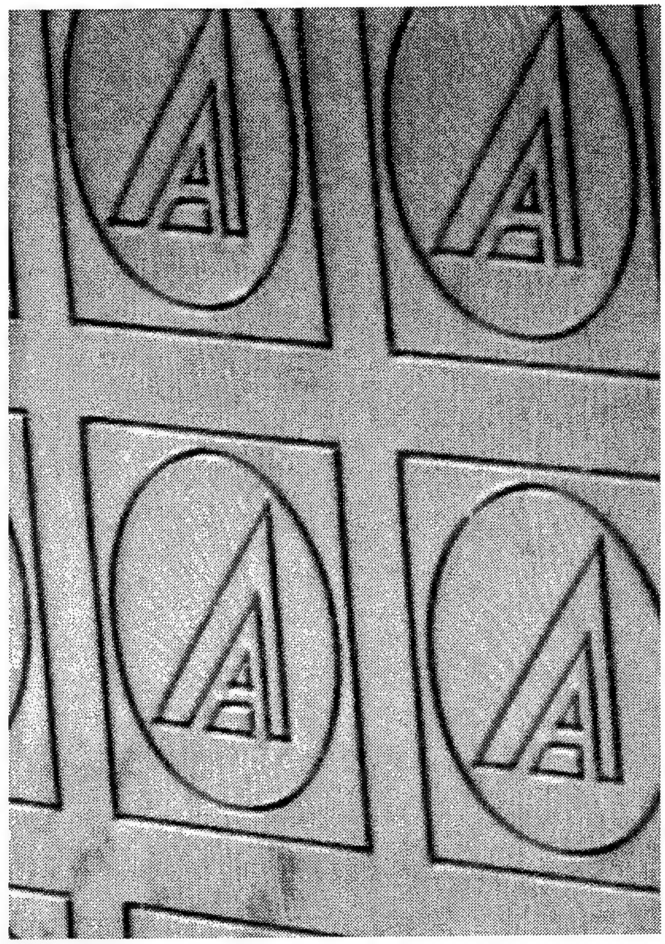


Figure 4. SEM photograph of laser-exposed Foturan with subsequent processing. This pattern tests the stability and controllability of the motion platform as it undergoes rapid acceleration; e.g., creation of right and acute angles while maintaining a constant linear speed of 800 microns per second for uniformity of exposure. See text for dimensions.

Thruster and component development was carried out in the following manner. We measured thrust produced by a bi-directional cold gas microthruster that incorporated two EG&G IC sensors Model 4425-15 silicon microvalves in the propellant feed system (one for each direction). The microvalves are a major flow impedance; at 20 psi feed pressure, the thrust level was 4.5 mN with no valve and 0.9 mN with the valve. The

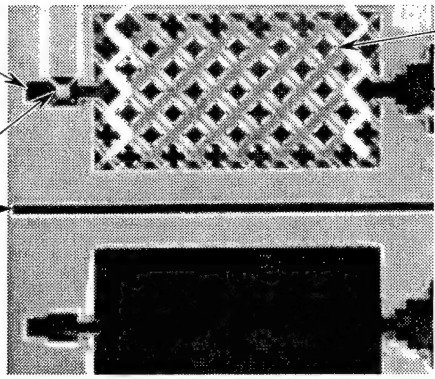


Figure 5. Photograph of part of the resistojet die after etching. The plenum resistor is a patterned polysilicon sheet sandwiched between two patterned glass layers. The plenum is 1.2 mm long and the heating element is less than 1 micron thick.

electrothermal valves also proved to be sensitive to propellant inlet temperature and forced convective cooling rates.

We had a number of micro-to-milli-Newton thrust resistojets fabricated by the metal oxide semiconductor implementation service (MOSIS). These thrusters were designed for a 2-micron complementary metal oxide semiconductor (CMOS) process followed by a post-fabrication etch in ethylenediamine-pyrocatechol (*EDP*) to create fluid flow structures. Figure 5 shows an etched "rocket chip". We discovered that a number of design changes were needed to strengthen the trampoline-like heating structures in the microresistojet plenums. We redesigned the resistojets and resubmitted them to MOSIS along with additional chips that contain prototype ion engine components.

Our micro ion propulsion systems are based on field emission and field ionization. The impact of surface roughness on field emission efficiency for a single field emitter was measured using a single Foturan pyramidal tip that was "baked" to enhance surface roughness at the microscale. Our data look very promising because nearly 300 nanoAmps were measured using only a 5 volt potential (at 10^{-7} Torr vacuum) between the tip and a nearby electron collector. This result was striking because the net electron current was 10–100 times greater than that reported in the literature for other uncoated tips and because relatively high currents are measured at the modest 5 volt input. Most field emitter tips require 50-to-100 volt potential difference, which is much higher than typical 5 V or 3.3 V digital logic levels. A more refined experiment is being developed that will not only measure the total current but also permit lifetime tests to be conducted.

Microthruster development will continue next year leading to micro-ion engines and CMOS-compatible resistojets with integrated sensors and silicon wafers or other media to ensure physical, as well as functional, compatibility between the subsystems.

The Task 4 goal is to develop a design methodology appropriate for mass-producible nanosatellites. A team of subsystem experts has been assembled, and a number of team meetings were held. The preliminary findings of the team indicated that much work needs to be done to build up the databases, the models, and the empirical relationships that would be necessary for the conceptual design capability. In addition, questions about the feasibility of wafer scale integration, the underlying technology for silicon nanosats, were raised. Based on this, it was decided to continue the effort by moving away from wafer scale integration and concentrating on nearer-term technologies, consisting of assembling printed circuit boards (PCBs) or multichip modules (MCMs) into a nanosat. The goal will still be to maximize the use of MEMS devices to maintain a 1 kg weight limit, but with technologies that are presently better developed and understood.

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1. Hansen, W. W., S. W. Janson and H. Helvajian. "Direct-Write Microfabrication of 3D Structures in Lithium-Alumosilicate Glass." *SPIE Proc,* **2991**, 104 (1997).

Exploitation of Commercial Microelectronics for Space Applications

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The decline of the DOD budget and subsequent consolidation of the defense industry infrastructure has resulted in the departure or down-scaling of a number of suppliers of radiation-hardened microelectronic components. Furthermore, acquisition reform initiatives and the proliferation of commercial satellite systems have increased interest in the exploitation of commercial microelectronics for space systems. This interest

stems from the perceived advantages of increased performance, lower cost, standardized parts, and increased availability.

This Corporate Research Initiative was begun in FY96 to identify and demonstrate approaches for incorporating commercial microelectronics technology into space systems while maintaining adequate levels of radiation tolerance and reliability. To achieve this objective, the program was structured to comprise the following five tasks: (1) determine the inherent radiation tolerance of selected, commercially-available standard products; (2) develop a cell library of robust, reliable, radiation-tolerant functional logic cells; (3) evaluate the radiation tolerance of commercial semiconductor fabrication processes; (4) develop a methodology and guidelines for quick-turnaround parts that are functionally and performance equivalent to radiation-hardened application-specific integrated circuits (ASICs); and (5) demonstrate the viability of commercial microelectronics for space applications through flight experiments.

In Task 1 we explored the feasibility of using commercial technology "as is" for space missions and successfully developed the methodology for subsequent testing of candidate integrated circuits for future space missions. During this fiscal year, we employed the Aerospace laser simulation facility to test an ASIC of interest to DOD space missions for susceptibility to single event latchup (SEL). This was the second generation of a device that had previously been tested in our facility. The previous version was found to contain many nodes sensitive to SEL at low latchup thresholds. The on-chip location of these nodes was provided to the ASIC designers, and the design was modified in an attempt to reduce its susceptibility to SEL. The new versions of the ASIC were found to be significantly less vulnerable to laser-induced SEL, demonstrating that commercial ASICs can be utilized in space missions when SEL-tolerant designs are employed.

During this fiscal year in Task 1, we also began tests of a commercial high-speed analog-to-digital converter (ADC). Several sources of ADCs were examined with a focus on devices of interest to Air Force programs; the devices chosen for characterization are produced by Signal Processing Technologies (SPT), with sample rates of 10^9 samples per second. The device is produced in both an 8-bit version and a 6-bit version. Although the 8-bit version is of more interest to military programs, it was found to be embedded in its package in a manner that was not conducive to laser test; i. e., the active regions of the ADC chip were not accessible to the laser light. However, the 6-bit version was found to be packaged in a manner that allows access to the active regions of the chip for laser excitation of single event effects. Since the 6-bit circuit is produced using the same emitter-coupled logic (ECL) technology as the 8-bit version, the tests of the 6-bit circuit should adequately represent measurements of device vulnerability to single event effects (including both SEL and single event upset (SEU)) for both the 6-bit and 8-bit versions. A single 6-bit device has been acquired along with an evaluation board. The device has undergone preliminary laser testing with more comprehensive high-speed testing planned for FY99.

A number of approaches are increasingly being used to incorporate commercial microelectronics into new space systems. In Task 2 of this program, we are investigating one of the most promising approaches, which involves designing integrated circuits from specially-crafted radiation-tolerant standard cell libraries utilizing commercial CMOS foundries for fabrication. In order to gain the advantage of using conventional commercial CMOS fabrication processes, these cells must incorporate special circuit and layout design techniques to reduce the impact of the space radiation environment on the device operation while having no impact on the manufacture of the device. An ASIC development capability is being developed in this task through the design and testing of radiation-tolerant standard cells, leading to a cell library of robust, reliable, radiation-tolerant functional logic cells.

The most compelling reasons to use selected commercial processes for spaceborne ASICs are their availability, low cost, and high performance. We have used the MOSIS silicon brokerage service, which makes several manufacturers' processes (e.g., Orbit, AMI, Hewlett-Packard, Vitesse, Peregrine, Taiwan Semiconductor) available to the microcircuit designer and allows low volume prototype development runs of a few tens of dice at a low cost. These commercial devices have very high performance due to the advanced state-of-the-art deep sub-micron processes employed to manufacture them.

This year we designed and tested an advanced version of an Aerospace test chip (RADCELL) for 0.35 μm design rules fabricated at several foundries through the MOSIS service. Single event latchup (SEL) testing was carried out both in the Aerospace laser simulation laboratory and using a heavy-ion cyclotron source to correlate data from the two testing approaches. We have also demonstrated the relative levels of SEL tolerance in four commercial CMOS foundry processes. Of the technologies tested, the Hewlett-Packard (HP) 0.5-μm CMOS process was found to have the highest intrinsic single-event latchup threshold (60 MeV-cm^2/mg linear energy transfer (LET)) followed by the HP 0.35 μm process (30 LET). These high thresholds indicate that the HP process is intrinsically immune to SEL for many space applications. We have utilized several design techniques to further minimize the susceptibility of these technologies to latchup, including excess spacing between devices in the integrated circuit, as well as the

Table 1. Summary of parameters that describe the spatial uniformity of minimum geometry NMOS and PMOS transistors from a single wafer processed at the Hewlett-Packard 0.5 μm foundry.

	Mean	Standard Deviation	Maximum	Minimum
NMOS Threshold Voltage (mV)	727.66	11.22	755.27	712.98
PMOS Threshold Voltage (mV)	901.43	24.51	951.01	868.17
NMOS Max. Drive Current (μA)	282.15	5.66	293.67	272.75
PMOS Max. Drive Current (μA)	119.38	3.20	123.92	111.58
NMOS Max. Transconductance (μS)	23.44	0.58	24.86	22.60
PMOS Max. Transconductance (μS)	6.64	0.15	7.02	6.36
NMOS Subthreshold Slope (mV/dec)	85.90	0.90	87.62	84.38
PMOS Subthreshold Slope (mV/dec)	87.15	1.29	90.22	85.05

insertion of n+ and p+ guard bands in critical regions in the integrated circuit. The p+ guard band approach was found to be most effective in raising the threshold at which latchup was triggered for all technologies. Furthermore, it has been shown that, by the judicious use of either increased device spacing, a single guard band, or two guard bands, single event latchup thresholds can be "tuned" to mission requirements, saving valuable layout area and complexity.

The data collected from this work was then used to guide the design of radiation-tolerant standard cells for the new HP 0.35μm process. Due to its high performance, this process was selected to implement an inverter, NAND gate, NOR gate, and buffer. These circuits will undergo latchup testing in the coming year.

In Task 3, we continued our evaluation of the total-dose radiation hardness of commercial CMOS manufacturing processes. Previously we had measured the total-dose hardness of four different CMOS technologies available through the MOSIS foundry service, and found that as the device technology was scaled toward shorter channel lengths, the inherent hardness of the gate-oxide improved. Furthermore, an evaluation of one technology in particular, the HP 0.5-μm process, showed the process to be total-dose hard to doses of interest to most commercial and some DOD satellite systems (above 100 krad). For this process, we showed that, after a total dose of 300 krad, the shift in threshold voltage was less than 50 mV, the off-state drain current was less than 10 nA, and measurement of field-oxide test structures indicated the field oxide did not invert. These results confirmed that the potential use of commercial technology for space applications is not only realistic, but that a 100 krad commercial technology exists today.

Because of the promise shown by the HP 0.5-μm process for the fabrication of radiation-tolerant integrated circuits, we have expanded our investigation to include a complete wafer run of this process. Twenty 6-inch wafers were fabricated at HP through the MOSIS foundry services. Included in each reticle cell were an updated version of our RADCELL, test structures from collaborating organizations, the MOSIS process monitor cell, and a Very Large Scale Integrated (VLSI) circuit function. The VLSI test circuit is a 500 MHz digital correlator targeted for use in a NASA radio astronomy application; this circuit will provide critical information regarding the scalability of our RADCELL total dose tolerance results to complex integrated circuits. One measure of the quality of a CMOS foundry is the spatial uniformity of device characteristics across a wafer. We have measured nearly 1000 transistors across a single 6-inch wafer. For each transistor, the threshold voltage, subthreshold slope, maximum transconductance, off-state drain current, and maximum drain current were measured; the spatial uniformity of these parameters across the wafer was excellent and they are summarized in Table 1. For example, the mean threshold voltage for NMOS minimum geometry transistors was 728 mV, while the distribution in threshold voltages as described by the standard deviation was 11 mV, which is only 1.5 percent of the mean. Similarly, the variation in maximum drive current for NMOS minimum geometry transistors was measured to be only 2.0 percent across the wafer. Similar results were obtained for minimum geometry PMOS transistors. Die of the 500 MHz digital correlator VLSI test circuit were provided to our collaborator, Spaceborne Inc., for packaging. The functionality of this circuit was verified, and development of test fixtures to assess the functionality of the circuit with increasing radiation doses was completed, with testing scheduled for next year.

To further extend our evaluation of the radiation tolerance of advanced commercial CMOS processes, we have recently characterized the radiation tolerance of two lots from the newly available HP 0.35 μm process after exposure to total ionizing radiation. The threshold voltage shifts associated with the gate oxide were shown to be small, consistent with previous measurements on commercial processes and with the scaled gate oxide. Measurements on various ring oscillators indicated no change in gate delay or power with exposure to radiation, consistent with minimal shifts in

transistor threshold voltages. However, a discrepancy was observed between the two lots for NMOS minimum geometry transistors. A third lot of HP 0.35 μm test structures is in the process of being evaluated, in addition to a pre-release lot of another advanced 0.35 μm process from Taiwan Semiconductor. Our work on advanced technologies continues to support the point of view that, as CMOS technologies continue to advance and devices continue to be scaled with associated increases in integration level, the total-dose radiation properties of these technologies make them candidates for insertion into space missions.

The objective of Task 4 is to ascertain the degree to which integrated circuits from a commercial foundry with a quick turnaround capability can mimic the performance of integrated circuits from a radiation-hardened foundry process. These prototype circuits could be used by system contractors to verify system performance prior to the availability of the radiation-hardened circuits that will ultimately be used in the system. Among the benefits of this task to space systems are reduced cycle time, earlier software checkout, and reduced cost.

Chip Express was chosen as the commercial foundry for this investigation because of their capability to deliver parts in 1–2 weeks after receipt of a given design. Honeywell was chosen as the rad-hard foundry because of the availability of their rad-hard design library and their Test Characterization Vehicle (TCV), which Aerospace has in-house. Over the last two years, portions of a Honeywell TCV were replicated in a design developed by Aerospace engineers to evaluate the performance of Chip Express circuits. The circuits were first simulated and compared favorably to the Honeywell circuits' timing performance and power consumption. The chips were then fabricated at Chip Express, tested for functionality and performance, and compared to the simulated characteristics. The tested parameters are actually better on the test chip than the stated simulated parameters. This is because the specifications from Chip Express reflect worst-case parameters due to differences in manufacturing lots. The performance measurements demonstrate that Chip Express circuits meet or exceed all specified values and are within worst-case tolerance of the Honeywell technology.

Over the last year, Chip Express stated their intent to make their chips available to the space community because preliminary test results show their product to be naturally hardened to total dose effects. To verify these results and compare the radiation tolerance of Chip Express devices to those we have tested from other commercial foundries, the necessary bias boards were built for testing the Chip Express parts in the Aerospace Co^{60} radiation source; testing will be completed early next year.

In Task 5, the spaceflight demonstration of commercial microelectronics has been accomplished through participation in experimental testbeds. The Naval Research Laboratory's Microelectronics and Photonics Test Bed (MPTB), which incorporated two Aerospace experiments, was launched in November, 1997. The first experiment utilizes field programmable gate arrays (FPGAs) manufactured by the Actel Corporation. The second experimental board characterizes Analog Single Event Upset (ASEU), which manifest as transients on the outputs of comparators and operational amplifiers commonly used in spaceflight hardware. Data obtained from this mission to date show that the device types are performing generally as predicted by ground testing; however, the single event error rate exhibited by the Actel devices is significantly lower than expected. This is due to the presence of metal strengtheners that were added to the testbed late in integration and lie across the devices under test, acting as additional radiation shielding and lowering the error rate. During the coming year, additional data will be obtained and analyzed, leading to a better understanding of the spaceborne performance of these devices.

During FY98, we also delivered an analog SEU board and a low-dose-rate experiment for integration into the Space Technology Research Vehicle (STRV-1d). This experiment combines the measurement of output transients in analog devices due to SEU with a dose rate experiment on the same device types. The devices being evaluated have been shown to experience analog SEU as well as to exhibit unusually large degradation in the input bias current and offset voltage at lower radiation dose rates; this effect is known as ELDRS (enhanced low dose rate sensitivity). Since this phenomenon calls into question standard ground-based testing procedures, the data collected from these experiments serves not only to demonstrate how these devices perform in the space environment but also to validate the ground testing methodology. It is expected that the STRV-1d will launch in the latter half of 1999.

In summary, this multi-faceted program has resulted in an in-depth understanding of the performance of several commercial technologies, including the identification of at least one radiation-tolerant commercial manufacturing process. Additionally, approaches to further enhancing the radiation tolerance of commercial microelectronics, particularly single event effects, have been developed. These results have placed Aerospace in a leadership role in the space microelectronics community as programs face the challenge of procuring radiation-tolerant and reliable integrated circuits in an environment of a shrinking radiation-hardened device market and revolutionary changes in program procurement practices.

Airborne Hyperspectral Imager (AHI)

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This is the second year of a two-year program whose goal is to establish a facility for collecting and analyzing infrared hyperspectral remotely-sensed data. The Airborne Hyperspectral Imager (AHI) facility uses the Spatially-Enhanced Broadband Array Spectrograph System (SEBASS) as its sensor. The SEBASS is a hyperspectral imaging instrument that operates in the MWIR (3 to 5 μm) and LWIR (7 to 13 μm) infrared spectral regions.

The SEBASS sensor is still the only airborne imaging hyperspectral instrument that covers the entire MWIR and LWIR atmospheric transmittance windows simultaneously. Since its first use in October 1995, SEBASS has been employed in over a dozen field campaigns to explore the utility of infrared hyperspectral techniques for detecting and characterizing gas plumes, for locating and identifying camouflaged targets, for surface material identification, for mineral exploration, and for studies of atmospheric compensation techniques.

During FY97, the first year of the AHI project, we constructed and flight-tested a stabilized platform that uses a differential GPS receiver and fiberoptic gyroscopes to provide geolocation information for the SEBASS sensor. This new SEBASS platform also allows more frequent on-board calibration, which has improved data quality significantly. In addition, we began to develop a computer application known as "Spectral Exploitation using Automated Logic" (SEAL). SEAL is a system that is specifically designed to ingest, correlate, and catalog large quantities of data. Its first application will be to the large SEBASS data set, which already contains more than 500 Gbytes of data. SEAL includes autonomous and on-demand operations for data processing, such as data conversion, calibration, analysis, processing status, and availability. It also performs system management tasks, such as system state-of-health, disk usage, and system errors. The goal is to build a system that requires little operator intervention once a simple operating script has been customized for a particular application. A Preliminary Design Review (PDR) for SEAL was held in January 1997 followed by a Critical Design Review (CDR) in April 1997. Detailed development of the software began after the CDR.

We set ourselves four major tasks for FY98. The first and largest task was to complete SEAL Version 1.0. The second and third tasks were to adapt our atmospheric compensation algorithm to meet SEAL interface specifications and to continue development of quantitative retrieval of gas column densities. Finally, we planned to finish developing the software and hardware required for georeferencing the SEBASS data.

Most of the effort during the second year of the AHI project was focused on implementing the SEAL application. Figure 1 is an overview of SEAL. There are three major components in SEAL Version 1.0; the Supervisor, the Database, and the User Interface. A fourth component, View, which is designed for on-line browsing of processed data, will be added to Version 2.0.

The SEAL Supervisor provides automated control of scheduled and event-driven tasks. The Supervisor initiates the other components, provides SEAL system management, and monitors the state-of-health of SEAL and of the host computer workstation. Because the Supervisor is implemented in the Java programming language, it will operate on a wide range of host computers. This platform independence is expected to extend the life of the overall SEAL application, allow the migration of SEAL to other platforms, and in the long term, enable SEAL to be applied to data sets other than SEBASS.

The inclusion of the Database component sets SEAL apart from competing data processing applications. The Database includes sensor and processing "metadata" (information in addition to the basic data sets) that comprise all known information about the data sets as they pass through various processing stages. The metadata includes pointers to raw data, ancillary information about the data (noise level, wavelength calibration, etc.), information about the data source, such as the type of targets in the scene, and geographical data. The metadata also includes a full record of processing history, the availability of data products, and data distribution. These features are designed to facilitate the use of SEBASS data products by East coast and West coast users who need to communicate the fruits of their work between themselves so that they can deliver data products to their customers in a timely fashion.

The third component of SEAL Version 1.0 is the User Interface, which is designed to provide an intuitive Graphical User Interface (GUI) to the SEAL system. The User Interface will allow a SEAL user to develop processing scripts for specific applications, to request that data and algorithms be imported and exported, and to make database queries to the relational database. The design of the GUI is such that a user does

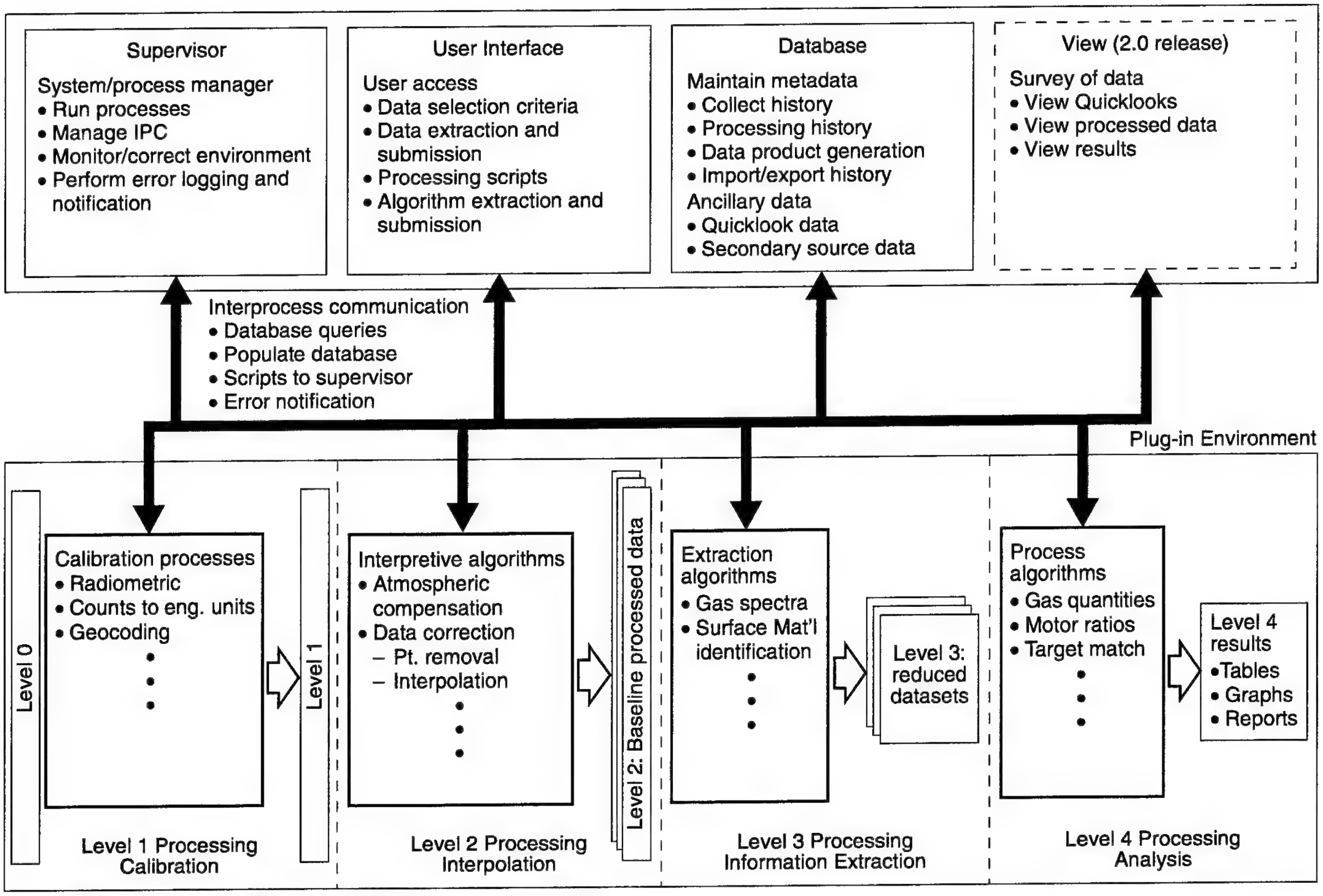

Figure 1. The architecture of SEAL Version 1.0 contains three basic components: the Supervisor, the Database, and the User Interface (the View component is scheduled for inclusion in Version 2.) The Supervisor provides automated control of scheduled and event-driven tasks; it initiates the other components, manages the system, and monitors system state of health. The Database component is a novel aspect of SEAL. It contains sensor and processing "metadata", including pointers to raw data, ancillary information about the data (wavelengths, noise, etc.), geographical information, and data processing history. The User Interface is designed to provide an intuitive Graphical User Interface (GUI) to the SEAL system. It allows the user to develop processing scripts, import and export data, and query the relational database. The GUI is designed so that the user can process SEBASS data without having to be an experienced computer programmer.

not need to be a computer programmer to process SEBASS data.

All of the SEBASS data collected this year were processed to Level 2 (radiometrically calibrated and regridded to a common wavelength scale) using automated algorithms that were designed for SEAL. The SEBASS data products were generated within two weeks of return from the data collection. This is especially impressive when it is realized that the data sets were each 50–100 Gbytes in volume. Currently, SEAL Version 1.0 is being tested before its expected final release in early October 1998. This release version will support full implementation of scripted data processing from raw data through Level 2 from the GUI with archiving of the results in the SEAL database tables.

The second and third tasks were directed at improving specific data processing algorithms. We have now developed our In-Scene Atmospheric Compensation (ISAC) algorithm to the point that we can apply it routinely to SEBASS data sets. This algorithm takes as input radiometrically-calibrated airborne SEBASS data and gives as output an estimate of the radiance that would be measured at the ground. It also estimates the atmospheric transmittance and upwelling atmospheric radiance as a function of wavelength. One of the lessons learned from our investigation of atmospheric compensation in the infrared is that models such as MODTRAN are not capable of making a priori estimates of atmospheric transmittance and emittance to the 0.1 percent or better accuracy required for the high-signal-to-noise ratio LWIR SEBASS data; only in-scene techniques can do this.

We also spent significant effort developing methods for the quantitative retrieval of gas column densities.

One key to success has been in finding ways to estimate the spectra of materials that lie under gas plumes of interest. We now have two working techniques. The first uses a "supervised" (operator-guided) method to find in-scene background spectra; the second is an "unsupervised" (automatic) method. Because these "end-member" selection techniques are central to several of our high-level algorithms, we are actively investigating other methods. We further extended our gas plume detection techniques by developing a "Bayesian" statistical method that allows us to test for the presence of trace gases in plumes. Because the algorithm effectively has a "penalty function", as each new gas is added to the hypothesized mixture, the fit must be increased significantly if the algorithm is to give a high probability that that gas is actually present.

The fourth task was to improve the hardware and software used to geo-reference SEBASS data. We improved the performance of the roll stabilization stage by increasing its bandwidth through the use of a dedicated microcontroller. This upgrade reduced the jitter from about 1 pixel (1 milliradian) rms to less than 0.3 pixels rms. This improves the aesthetic appearance of the SEBASS data strips and gives more accurate geolocation.

Our georeferencing software effort has centered upon combining information from an on-board differential GPS receiver, a three-axis fiber-optic gyroscope that is mounted on the SEBASS roll-stabilization platform, and SEBASS timing to derive the geographical location where the SEBASS sensor line of sight of each pixel intersects the surface of the earth. Processing the georeferencing data has four distinct steps. First, data from the GPS, gyroscopes, and SEBASS clock are merged to a common time. Next, because the gyroscopes give only differential information, the gyroscope data are integrated using quaternions. Then, known positions in the SEBASS scenes are used as reference "tie points" to set the zero point for the gyroscopes. Finally, we derive the line of sight for every data line for all 128 cross-track pixels in the SEBASS data. The geographical information is saved as metadata in the SEAL database.

In summary, the development of SEAL and its associated algorithms has already resulted in a significant reduction in the time required to calibrate and deliver SEBASS data. Before this year, it was taking 6 to 12 weeks to calibrate a data set; this time has been reduced to 2 weeks. Now that SEAL Version 1.0 is on-line, we expect that the time and effort required to calibrate the data will be even shorter. This, combined with the SEAL database and new processing algorithms, will allow us to put more effort into delivering useful data products to our customers. Last, our newly-developed ability to deliver georeferenced data will make SEBASS data even more valuable to customers who are interested in applications such as mineral exploration.

Reusable Launch Vehicle Capability Development

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This report covers progress made during the first year of Reusable Launch Vehicle (RLV) tool development, modeled after the approach taken in the development of Aerospace's Concept Design Center (CDC). A team consisting of Aerospace personnel representing various disciplines of RLV concept design and analysis was assembled. The RLV disciplines represented include: aerothermal, cost, economics, ground/operation, performance, propulsion, systems, and vehicle configuration. A point of contact acts as the lead developer for each discipline, with multiple people from the same area of expertise supporting the development of the models. Each team member presented a list of model development and model enhancement tasks that would be required to develop an integrated RLV design and evaluation process. The accomplishments in each discipline during the year are discussed below.

Three FY98 tasks were completed in aerothermal technology development for reusable launch vehicles: (1) identification of critical technologies; (2) development and verification of aerodynamic tools; and (3) development and verification of thermal tools.

The identification of critical technologies was necessary for determining which aerothermal tools are required, isolating those tools already available at Aerospace that are ready to be used, and focusing on existing tools to be enhanced or new tools to be acquired. The capability to quickly generate numerical grid meshes for detailed analysis of flow around complex RLV geometries is critical in using computational fluid dynamics (CFD) tools for rapid assessment of RLV concepts. Aerodynamic analysis tools that specifically address glide and powered flight are also critical. While accurate determination of aerodynamic characteristics

such as lift, drag, moments, and flight stability is not as important for traditional expendable vehicles, it is crucial for RLVs. Similarly, more robust aeroheating and base heating analysis tools are critical for handling RLV-specific features such as ramjet/scramjet inlet flows, boundary layer transition on arbitrary vehicle shapes, multi-engine plume heating during ascent, and base heating during powered descent and landing.

In general, rapid aerodynamic design assessment depends not only on appropriate analytical tools but also on a good ground and flight database. Such a database, biased towards RLV-like configurations, has been assembled. GRIDGEN, a fast and versatile numerical grid generation code for CFD analysis, was acquired and tested on a typical three-dimensional launch vehicle geometry. We plan to apply it to specific RLV configurations in FY99.

APAS, an aerodynamic code acquired from NASA/LaRC, has potential for use as a rapid design tool. However, this code relies on slender-body and thin-airfoil theory, and therefore needs to be modified to handle the much blunter RLV configurations. To accomplish this, an APAS source code was recently acquired from NASA/LaRC. In FY99, information from the aerodynamic database will be used to increase APAS' capability to handle blunter configurations. It was also determined that there is a need to improve its user-friendliness in the areas of Input/Output (I/O) and pre- and post-processing. Tektronix terminal emulator software is being acquired to improve APAS' I/O capability on the much faster Silicon Graphics workstation.

A relatively fast CFD/aeroheating code called GASP was acquired and implemented for a typical three-dimensional launch vehicle configuration. Other aeroheating codes acquired from NASA/LaRC and evaluated for simplified geometries are MINIVER II, LAURA, LaTCH, and ThinBL. More work is required to evaluate and modify this later series of codes to handle complex, full vehicle configurations. To perform the thermal analysis, the propulsion team is expected to provide engine and propulsion parameters as inputs that will be used to size the thermal protection system (TPS) for the vehicle base region.

Significant progress was made in the development of an Excel-based spreadsheet version of the in-house Launch Vehicle Cost Model (LVCM) during FY98. The LVCM is planned for completion in FY99. Also, literature research was conducted in regard to developing cost estimating relationships for air-breathing and combined cycle engines. These relationships will be incorporated into the Launch Vehicle Cost Model in FY99. In FY98 we also generated an interface matrix showing input/output relationships between the RLV cost models and the RLV subsystem/system modules.

Our primary emphasis in the area of ground systems and operations was to enhance the fidelity of the algorithms in the operations design model. This allows for a more accurate representation of vehicle turnaround time and vehicle reliability based on vehicle design inputs. Specifically, algorithms relating the impact of design/operating margins on launch processing operations and the probability of vehicle failure were enhanced. The model's ability to handle new technologies related to the RLV configurations such as reusable cryogenic tanks and advanced TPS were also updated. This effort focused on developing a capability to analyze single-stage-to-orbit vehicles and is now operational.

The effort also involved developing a new model called SpaceFleet to replace Starfleet. This will provide a significant increase in our capability to simulate a wide variety of launch processing scenarios, including both vertical and horizontal vehicle processing and takeoff/landings. A graphic user interface that integrates the Starfleet/SpaceFleet models with the operations design model was completed. It was developed using Visual Basic and provides a menu-driven program that incorporates standard window screens for user input and interaction. The user can move seamlessly between the models.

Four FY98 tasks were completed in performance development for reusable launch vehicles: (1) land overflight and casualty minimization methodology; (2) RLV flight design and modeling; (3) trajectory-based engine models; and (4) aeroperformance design tool.

A high resolution population database was incorporated within the trajectory performance model (Generalized Trajectory Simulation—GTS). A methodology—Trajectory Based Population Safety Model—for calculating the expected casualty and individual risk was devised and implemented. Preliminary tests of optimal vehicle steering to meet minimum casualty expectation values have been performed for ascent and reentry missions.

The trajectories of several new RLV configurations were modeled, with special attention to takeoff, cross range flight, reentry, and landing simulations. Some of these simulations required writing of new flight control routines and collection of aerodynamic data.

Existing airbreathing engine models in GTS were reviewed and found to be quite limited. New models were developed and incorporated into GTS. Generic model input/output requirements were defined for the propulsion and aerodynamics modules.

We developed an analytical methodology for evaluating the subsonic aerodynamic characteristics of blunt-based lifting-body and wing-body reentry vehicle configurations. This tool, built upon flight data from seven full-scale RLV-type vehicles, will be useful in assessing and validating the subsonic performance of new lifting reentry RLV designs.

Four FY98 tasks were completed in propulsion development for reusable launch vehicles: (1) A generalized liquid rocket engine performance code for preliminary engine sizing was completed. The model was checked for two propellant combinations, LOX/Hydrogen and LOX/RP-1, and will be expanded to include others. (2) A detailed engine balance model for gas generator cycle was completed using LOX/Hydrogen. A generic expander cycle model utilizing RL-10 engine characteristics was also completed. (3) A flexible Ramjet/Scramjet Engine Simulation Program (RAMSCRAM) by NASA Lewis was obtained and installed at Aerospace. This model will be used to calculate the performance, flowrates, pressures, and temperatures for ramjet, ejector-ramjet, and scramjet for LOX/Hydrogen, LAIR/Hydrogen, and Air/Kerosene fuel. A ramjet weight model was also obtained from the Georgia Institute of Technology through Aerojet. (4) In-house airbreathing propulsion models including inlet sizing, combustor performance, and nozzle performance have been retrieved and are being evaluated.

Only minor modifications were made to the vehicle configuration models. The existing models are at a higher level of fidelity than the other disciplines, and therefore only minor funding was set aside for model development in this area. Once the fidelity of the other disciplines surpasses that of the vehicle configuration models, these models will need to be enhanced.

The integration of the models into one RLV design analysis "package" presents a technical challenge due to the fact that not all of the models will be housed on the same platform (such as Excel). In order to integrate the models and to develop a formalized method of information transfer between all the models, a "test case" vehicle was run through the design/analysis process. The "test case" chosen was a 10,000 lb. vertical takeoff vertical landing (VTVL) single stage to orbit (SSTO) vehicle, similar to the McDonnell Douglas DC-X. By pushing this case through the process, the model interactions were better understood and an integration plan was formulated. This integration will be the first task for next year's program.

Corporate Strategic Initiatives

Microelectromechanical Systems (MEMS)

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A basis for spacecraft component size and weight reduction was realized with the emergence and maturation of the area of micro/nanotechnology (MNT). Application of batch-processing, advanced microelectronic packaging/fabrication techniques, and microelectromechanical systems (MEMS) components can further reduce spacecraft cost and increase reliability. In 1993, these advantages were recognized at Aerospace and efforts were initiated to insert MEMS technology into military spacecraft systems. MEMS first evolved into ASIMs (application-specific integrated microinstruments)—a modular integration of all necessary elements (memory, power, communications, etc.) as a standalone microinstrument, and ultimately into the silicon nanosatellite—a revolutionary system concept invented at Aerospace based on an assemblage of silicon wafer ASIMs. Complementary to the existing Corporate Research Initiative "Microtechnology for Space Systems," this Corporate Strategic Initiative was funded in FY98 to further corporate goals beyond MEMS insertion and to specifically address nanosatellite and microsatellite systems concepts.

Within Aerospace, the term nanosatellite refers to a 1-kilogram-class spacecraft fabricated using modified wafer-scale semiconductor batch-processing techniques. Batch fabrication allows creation of highly-integrated systems-on-a-wafer, which can drastically reduce the total number of piece parts and labor required to assemble a fully-functioning satellite. Figure 1 shows an artist's conception of a silicon nanosatellite designed as an assembly of thick single-crystal silicon wafers that function as multichip modules (MCMs). Low-power digital circuits, low-power analog circuits, silicon-based radio-frequency circuits, and MEMS (such as thrusters and acceleration sensors) are routinely fabricated on silicon substrates. Silicon also serves as structure, thermal control system, radiation shielding, and transmissive optical material in the near infrared. This innovative paradigm of satellite design can enable distributed spacecraft and new space architectures.

The major effort this year focused on analyzing mission and nanosatellite spacecraft requirements for creating a kilometer-radius sparse aperture array as shown in

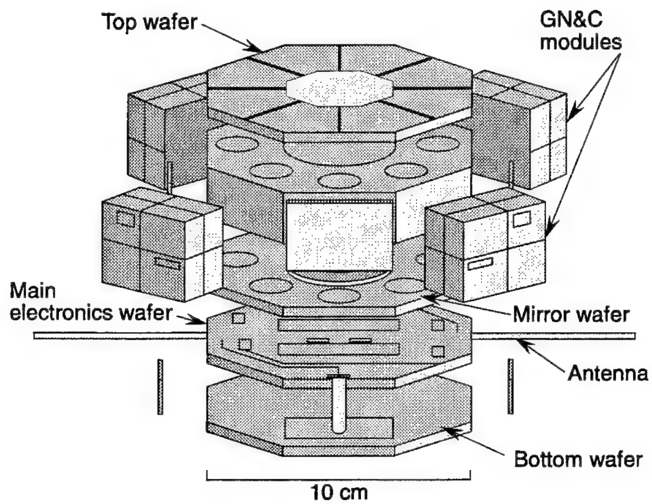

Figure 1. Exploded view of a conceptual silicon nanosatellite for low-resolution Earth observation.

Figure 2. Individual nanosatellites orbit about the central mother ship and function as individual radio frequency receivers that transmit real-time signals to a coherent signal combiner located in the mother ship. This approach does not generate the overall signal gain a conventional antenna of equivalent size would, but it does yield an extremely narrow main beamwidth with a very high angular resolution that can be used to image radio sources at VHF and UHF frequencies. We studied signal reception from individual ground-based sources transmitting 1 W at 300 MHz.

Maintaining a co-orbital configuration such as that shown in Figure 2 requires careful exploitation of orbital mechanics. Fixed formation flying about the mother ship leads to unacceptably large propellant requirements, even for mission durations as short as one year. If the cluster is allowed to rotate once per orbit about the mother ship and is confined to a plane whose normal is directed 30° above or below the nadir, the velocity increment is significantly reduced. Detailed analyses have shown that selection of a 63.4° orbit inclination and use of at least three micro-corrections per orbit can drop the yearly velocity increment requirement to the 10-to-30 m/s range for a 1-km radius cluster. This allows 10-year mission lifetimes of kilometer-scale arrays in low earth orbit and multi-100 km

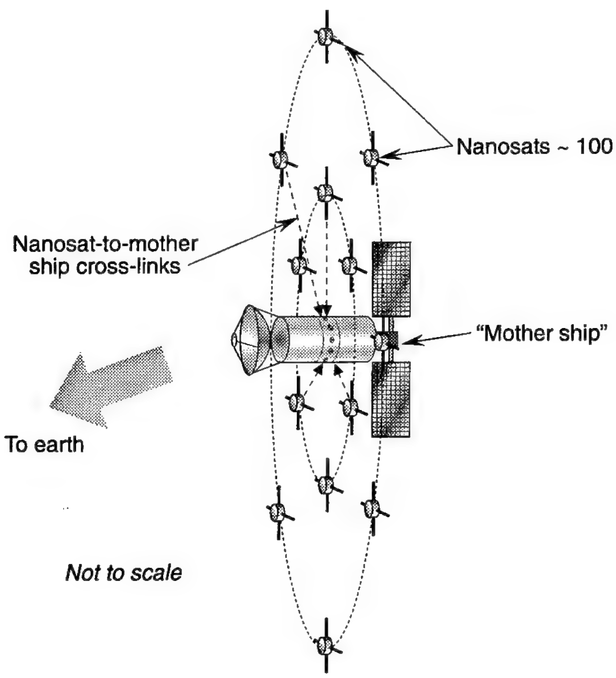

Figure 2. Nanosatellite sparse aperture array concept.

diameter arrays at geosynchronous altitude using cold gas or chemical propulsion for orbit maintenance.

A logarithmic-spiral distribution of nanosatellites about the mother ship was chosen to eliminate sparse-aperture grating lobes and to provide an aperture-illumination taper across the array. Side lobes cannot be eliminated and are typically much stronger in sparse arrays than in conventional antennas. Figure 3 shows the calculated far-field gain pattern produced by a 100 nanosatellite configuration with a 1-km radius if each nanosatellite has a dipole receive antenna. The main beam is very narrow, about 0.7 milliradian full-width half-max (about 0.04°), which will produce a 0.7 km diameter spot beam at a range of 1000 km. Significant

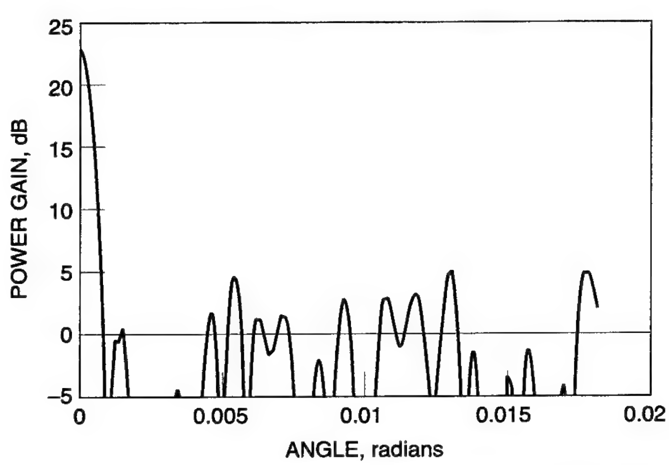

Figure 3. Antenna gain as a function of angle for a specific 100-nanosatellite sparse array with a radius of 1 km.

side lobe structure exists; the highest side lobe is 17 dB down from the main lobe and the average side lobe power level is 20 dB down from the main lobe. Applications that require 30 dB of side lobe suppression would require 1000 nanosatellites. We are currently looking for missions that can tolerate these high side lobe levels.

The orbiting sparse array nanosatellite system concept requires that the position of each nanosatellite, with respect to the mother ship, be known to about ⅛ of a wavelength (12.5 cm @ 300 MHz) and that the carrier wave be reproduced on the mother ship with equivalent time accuracy (0.4 ns @ 300 MHz). Position control, however, is not so stringent; 10 meter deviations are acceptable as long as position is known within ⅛ wavelength. We are currently investigating on-orbit differential GPS, rf beacons on the mother ship, and laser rangers coupled to star trackers for nanosatellite position determination.

The orbital mechanics simulations suggested that thrust vector knowledge, and hence nanosat pointing accuracy, be accurate within a few degrees. Attitude determination at the required 2° level can be accomplished using micromachined sun sensors, Earth sensors, and GPS carrier-wave phase measurement. Each nanosat is three-axis stabilized using magnetic torquers and thrusters. Radio frequency beam-steering is accomplished electronically, which eliminates the need for rapid slew maneuvers. Rotation rates are slow, about 4° per minute, and the nanosatellite moments-of-inertia are small enough to enable all-propulsive attitude control.

An optical cross link was chosen because it is extremely directional and fairly simple for km-long free-space distances. Two milliwatts of optical output power and a 1 mm aperture will create photon fluxes greater than 10^{12} photons per cm^2 within 25 cm of the center of the 1-meter diameter spot at a range of 1 km. Gigabit/second data transfer rates are possible using 1-cm diameter receive optics on the mother ship. Pointing accuracy for the laser cross-links is about 0.25 milliradians and beam steering up to ±10° in two dimensions is required to compensate for the attitude control range of the nanosat bus. Microelectromechanical beam steering systems placed between the laser diode and the final transmit lens are ideal for this application.

The mother ship is a conventional multi-kilogram spacecraft that contains nanosatellite cross-link receivers, the complex coherent signal combiner, and the downlink to Earth. Initial estimates of power and mass requirements for the coherent signal combiner indicate that several watts and several kilograms will be required for each nanosatellite channel. Sparse arrays using more than 1000–2000 nanosatellites will be impractical due to solar array size and the total system

mass on-orbit. We are currently refining these numbers to determine practical limitations on array population (numbers of nanosatellites) and hence ultimate main lobe to side lobe signal rejection.

Based on the previous considerations, it can be concluded that nanosatellite-based free-flying sparse aperture arrays can be used for missions that (1) require beam widths of less than a few degrees at VHF and UHF frequencies, and (2) can tolerate side lobe levels 20-to-30 dB down from the main lobe.

The objective of the Aerospace Technology Applications Microsatellite (ATAM) task included review of microsat technology to further MEMS space applications, to enhance Aerospace's image in microtechnology, and also to seek partnership opportunities. Drawing from the complementary microtechnology CRI program, the general objective was to steer research and development efforts toward effective insertion of MEMS and related microtechnology into new space systems, and to seek an initiative that could lead to an Aerospace microsat. A number of approaches were undertaken.

In FY97, a solicitation was sent out company-wide for proposed missions that would suit an Aerospace-initiated microsat. The 30 responses were narrowed to nine candidates by January 1998. Of these, only the Solar Storm warning microsat (SSμSat) gained expressions of interest from industry and the promise of possible partnerships in future commercially-operated low cost solar storm warning sentinels. Its merits lay in an advanced hemispherical imager being pursued by the astrodynamics staff at the University of California, San Diego. This imager could, in principle, track coronal mass ejections (CMEs) over most of the sky from the solar regions to near earth, and thereby provide unprecedented data for predicting the impact of geomagnetically induced currents on earth. The imager is small and requires little power. By locating it in halo orbit about the L1 libration point between earth and sun, the microsatellite would permit continual viewing of the sun. It would allow two to three days early warning of a solar storm, and if coupled with an on-board magnetometer would verify likelihood of the storm affecting the earth.

The Concept Design Center (CDC) staff was tasked with identifying limitations of the CDC databases for microsat conceptual design. After several CDC runs that underscored the dearth of databases for microsatellites, a true microsatellite configuration was achieved with a mass of about 75 kg, suited for launch to halo orbit via a Pegasus (see Figure 4). We estimate the nonrecurring cost of the SSμSat at about $6 million. While the satellite could benefit from MEMS (for example, a DARPA MEMS-based magnetometer) the mission does

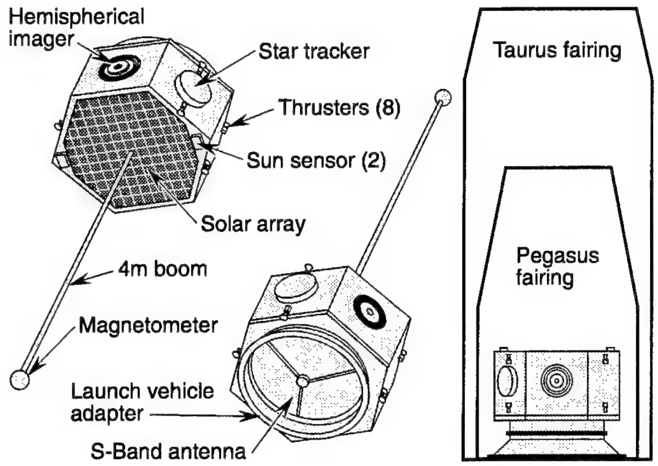

Figure 4. The Aerospace SolarStorm microsat concept.

not depend on MEMS technology. The SSμSat could be integrated by Aerospace and potentially lead to a consortium with affected utility and other industries (as well as the Air Force) that would launch periodic special-purpose replaceable microsats at affordable cost. In the course of this study strong interest in this imager was expressed by Air Force personnel at the Sacramento Peak Observatory of the National Solar Observatory. Meetings were held with experts in the area of solar storm effects from the utility industry as part of the follow-on plan for SSμSat.

The recommended follow-on activity, outside the scope of the proposed FY99 program, is to pursue USAF funding of the validation phases of the hemispherical imager, with Aerospace as designer and integrator of the operational SSμSat, followed by solidifying partnerships with industry.

The design work on SSμSat created an opportunity for Aerospace to respond to Vice President Gore's TRIANA mission for continual earth viewing from L1. A report submitted for an Aerospace-proposed combined mission (both earth and solar observatory) was very well received by NASA. A preliminary proposal was submitted in partnership with the University Space Research Association, a university consortium set up by the National Science Foundation. However, TRIANA did not win congressional funding support.

Stanford University's Space Systems Development Laboratory contacted Aerospace to implement a PICOSAT payload (<1Kg) on their OPAL satellite slated for launch in late 1999. A general plan was devised to use this as an opportunity to develop and fly DARPA MEMS technology, leading to future low-Earth orbit (LEO) networks of producible nanosatellites. The DARPA MEMS Program Manager strongly supported the idea, and is providing seed funding for Aerospace to perform GSE&I planning for such a mission.

Several other activities were pursued during FY98:

- Since very small satellites have limited space for body-mounted solar cells, a novel solar power concept (the Aerospace PowerSphere) for micro- and nanosatellites was developed utilizing thin-film solar cells on a deployable sphere that requires no orientation and can be sized to fit power needs. Models were built, and the concept, which has potential intellectual property rights for Aerospace, is being pursued in a separate IR&D effort in FY99.
- A partnership with JPL using their miniature GPS receiver in a close-coupled miniature integrated GPS and micromachined IMU was pursued as an extension of the FY98 GPS/IMU CRI task. The concept is for GPS to directly control any microsat with close-coupled MEMS micromachined IMU backup. Initial dialogs have been conducted with JPL, the Mayo Foundation, and the C.S. Draper Laboratory.
- The feasibility of gun launch of probes and small satellites based on the HARP Progam accomplishments of the 1960s was explored. Dialogs have been initiated with the Army Research Lab (Aberdeen) to evaluate possible approaches.

In summary, this year's CSI program has led to the preliminary development of the Aerospace silicon nanosatellite concept and its application in sparse aperture arrays (constellations). Future efforts will focus on other missions, and on fabrication, cost, applicability, and need. Subsystem development and breadboard verification will also be carried out.

Aerospace Technology Application Microsatellite efforts have identified several potential opportunities for MEMS component insertion and microsatellite development. Opportunities such as SSμSat and the DARPA-MEMS PICOSAT will be pursued further as will be other micro/nanotechnology, MEMS, and integrated microsystem opportunities.

Center for Orbital and Reentry Debris Studies (CORDS)

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The Center for Orbital and Reentry Debris Studies was established in June 1997 as a Corporate Strategic Initiative to focus Aerospace efforts in these important, emerging areas of interest to space users. In this first year of a three-year effort to substantially update and enhance Aerospace tools and capabilities, CORDS was provided with IR&D funds to sponsor related research and tool development. Activities supported ranged from a metallurgical examination of remains of a reentered satellite to development of new tools for analyzing the propagation of debris from on-orbit spacecraft explosions. CORDS has also purchased a state-of-the-art parallel processing computer that is being used to investigate ways to improve launch and on-orbit conjunction assessment capabilities.

In the next 9 years, over 2,000 new satellites are projected to be added to the approximately 10,000 tracked objects in earth orbit [1]. On-orbit explosions and anomalies are expected to increase the debris population by an even larger number. Constellations are being developed with as many as 88 spacecraft, 26 of these sharing the same orbit plane. Satellites are being placed in their final mission orbits using long duration, low thrust burns, which means that they pass relatively slowly through orbital altitudes where other spacecraft are operating. Near-Earth space is becoming crowded with orbiting objects.

The increasing use of space as we move to the new century has heightened awareness within DOD, NASA, NOAA, the commercial sector, and the international community of issues related to the generation and propagation of space debris, the potential hazard to spacecraft from debris as well as from other operating satellites, and the need for tools and techniques to predict and minimize hazards. In addition, government (both national and international) is developing policies designed to minimize the creation of new space debris. Further, the significance of reentry breakup has been elevated by the realization that this preferred method for eliminating space hazards—deorbiting hardware so that it will burn up in the Earth's atmosphere—may need to be done more carefully to avoid creating a hazard to people and property on the ground.

Space Debris: One of the first tasks performed was an analysis of real and anticipated needs of previous and potential future customers. This analysis was essential in developing a strategy for CORDS activities, and was the basis for a paper presented at the 1998 IAF conference [2] highlighting the current state of the art

During FY98, CORDS made substantial improvements to the Collision Vision analysis tool suite, and several independent validation efforts have demonstrated its accuracy. As Figure 1 illustrates, Collision Vision is an Aerospace-developed application that models close approaches of launch vehicles and satellites with other orbiting objects. Collision Vision has been applied operationally to numerous customer launches, through which Aerospace was able to clearly demonstrate the value of

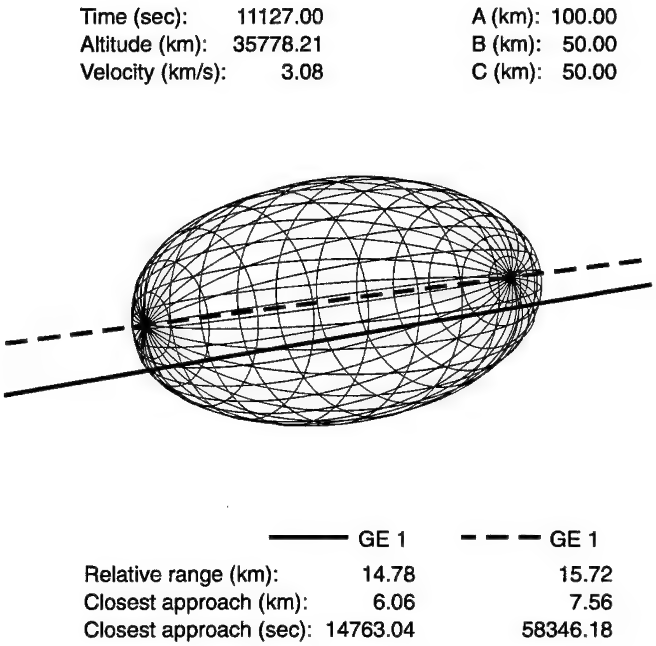

Figure 1. The conjunction of two satellites is illustrated here. Collision Vision tracks the propagation of satellites and accounts for uncertainty in their location by the elliptical shells.

higher-fidelity collision avoidance assessment. Collision Vision was also used to perform critical research in requirements analysis for several of our customers. Corporate recognition of the value of Collision Vision led to the specification, procurement, and installation of a CORDS Computational Facility in Colorado Springs. This state-of-the-art parallel processing facility and the Collision Vision software allows prediction of launch vehicle and satellite conjunctions for government and commercial customers.

A new statistical approach developed partly with CORDS funding was used to examine the potential for collision of space debris and catalogued objects with the tether lost by the Space Shuttle (Mission STS-75). The collision hazard for the mission was determined, and it was found that the tether/satellite system was subject to a number of small particle impacts while in orbit. Collision with larger cataloged objects was found to represent a negligible hazard. A paper on the results of this study was presented at the 49th International Astronautical Congress [3].

A method of calculating collision probability between two satellites given their state vectors was analyzed. The technique was coded and used on data from the first documented collision in space which involved the French Cerise satellite. The method has the advantage of not requiring state vector propagation and associated computation cost, which enables short run times on a PC-based tool.

The use of disposal orbits for geosynchronous satellites was examined and a post-mission disposal strategy was developed for ensuring a 300 km clearance above the geosynchronous altitude. This work was presented at the AIAA Astrodynamics Conference [4] and has been discussed with NASA/JSC representatives in discussions of evolving space policy related to spacecraft disposal.

Orbit Decay: As a result of the recent launches of Iridium satellites, along with a few government launches, an unusually large number of Delta II second stages (similar to that from which debris landed in Texas) have been decaying into the atmosphere. Since March of 1998 six second stages have decayed and at least two more will decay by January of 1999. This has provided a unique opportunity to exercise the orbit decay prediction methods developed at Aerospace. Using a recently-updated version of the Aerospace-developed LIFETIME code, predictions for the reentry time for each of these stages have been made at somewhat regular intervals. Based on the 24 reentry predictions, the mean error between the predicted and observed impact times was six percent of the time to impact, whether a week or an hour, with a standard deviation of four percent—excellent results for these types of predictions. Detailed comparisons like these are unique in the industry and will continue to be generated.

Reentry: A new state estimator has been developed to reconstruct trajectories for reentering space objects using sensor data. Preliminary studies show that the position and velocity estimates compare well to post-processed results. Additional work in FY99 will refine this methodology and review its applicability as a real-time analysis tool.

Aerospace completed a reentry breakup analysis of the Ariane 502 main stage launched in October 1997. A reentry observation project for this flight had positioned AST and ARGUS aircraft near the predicted Ariane 502 main stage breakup point to collect data during breakup and reentry. Because of a main stage performance shortfall, the breakup point occurred 4000 nm uprange near Papua, New Guinea and no data was collected by the airborne assets. Using other sensor data available to Aerospace, a detailed trajectory reconstruction and breakup analysis for the Ariane 502 stage was completed. The results were briefed to the Ariane 503 reentry observation team in Seattle as part of the planning effort for an upcoming Ariane 503 flight.

A Delta Stage 2 rocket body reentered over the central portion of the United States in the early morning hours of January 22, 1997. As this stage reentered the atmosphere traveling south it broke up over Topeka, Kansas at approximately 3:30 AM and released a debris stream that stretched 400 miles over Oklahoma and Texas. The recovered debris generated from this reentry included a small fragment weighing less than one pound, a helium pressurant tank weighing 66 lbs., and a

Figure 2. The 1997 impact of a 563 pound fuel tank 50 yards from a farmer's home in Texas was ample demonstration that space hardware can and does survive reentry. The tank was one of three recovered debris pieces from a reentering second stage that had been in orbit for 9 months.

fuel/oxidizer tank weighing 563 lbs (see Figure 2). The small fragment reportedly struck a woman near Turley, Oklahoma, but caused no injury.

This reentry provides a rare opportunity to develop a case that can be used to benchmark reentry breakup and hazard prediction tools. Such tools have proved to be somewhat inaccurate when applied to Space Shuttle external tank and other major reentry events. Accurate tools are essential to developing reliable predictions of spacecraft component survivability, useful when the spacecraft carries sensitive components or hazardous materials, or when predicting the potential hazard to people and property, or when designing space hardware to come apart in a predictable way during reentry.

Taking advantage of this opportunity, CORDS was able to have the recovered Delta Stage 2 rocket body debris delivered to Aerospace and has funded several tasks related to this reentry. The first involved a detailed investigation of the hardware to determine whether information could be learned about the heating experienced during reentry. A detailed metallurgical survey was conducted on the large stainless steel tank, and the results give a good indication of the maximum temperatures experienced by the tank. A survey and analysis of space debris/micrometeoroid impacts on the tank is also being conducted.

The second part of the study required that we reconstruct the trajectories followed by the reentering stage and each of the recovered debris pieces. This work encompassed both the on-orbit portion of the orbit decay—which lasted 9 months—and the actual reentry, which occurred over a span of 30 minutes. Reconstructed trajectories (see Figure 3) determined that breakup occurred between 41 and 44 nm altitude, and in all cases the tank impact location errors from the reconstructed trajectories were less than 6 nm when measured against the known impact location. This information will be published as a resource for the reentry community. The predicted heating environment experienced by the reentering stage was also documented. These predictions will be compared to the results of the metallurgical examination when it is completed.

Data useful for developing an additional benchmarking case was collected from several different sensor platforms for a recent reentry that had an unusually high velocity. Aerospace has been developing data fusion techniques to combine the observed data in order to get a better understanding of the reentry breakup characteristics for this event. Preliminary conclusions from this work indicate that in spite of the high reentry velocity, the vehicle did not suffer a catastrophic

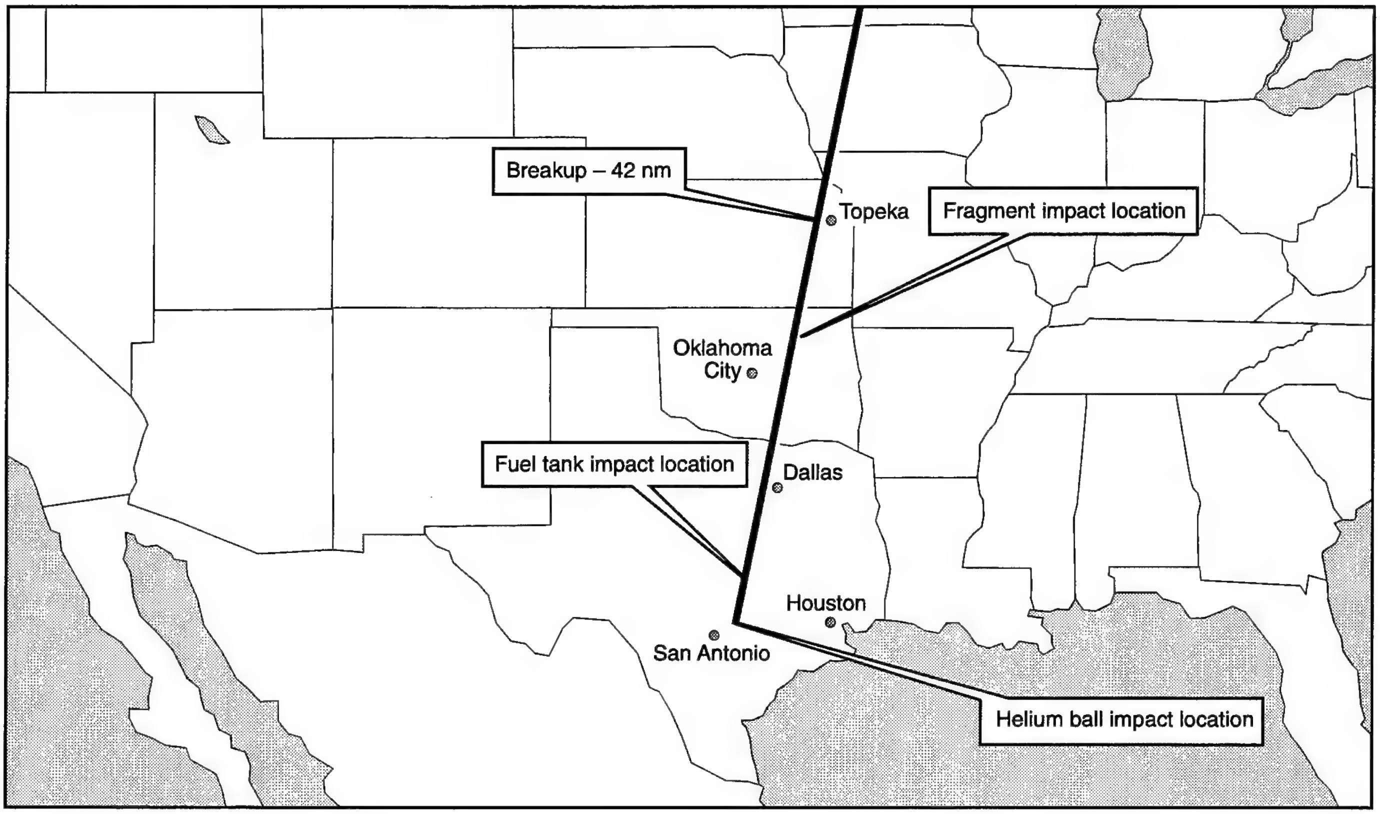

Figure 3. Reconstructed ground track for the Delta 2 reentry.

breakup until it was below 40 nm altitude. Work on this reentry is ongoing.

During the past year under the sponsorship of CORDS and the National Systems Group an empirical aerothermal model was derived for satellite breakup based on 1971 Vehicle Atmospheric Survivability Test (VAST) data. This model was then tested against recent satellite tests and found to agree quite well with the observed breakup. The empirical results were presented at the NRO's 5th Satellite Reentry conference [5].

A paper entitled "The Realities of Reentry Disposal" was presented at the 1998 AAS/AIAA Space Flight Mechanics Meeting [6]. The paper, which is based on space vehicle reentry breakup studies at Aerospace, served to alert the space community that space vehicle survivability of atmospheric reentry is greater than commonly believed. This information is relevant to space debris mitigation measures that employ random satellite reentry as an end-of-life disposal option.

Modeling radiant heat transfer among components of a reentering space vehicle was the subject of an analysis entitled "Fundamentals of Configuration Factors". The analysis included methodology to calculate radiative heat transfer configuration factors and suggested efficient computer implementation techniques. The objective was to improve the fidelity of reentry heating models and to achieve better agreement with reentry test data.

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Spacecraft and Launch Vehicles

Spacecraft Battery Performance Simulation System

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This project completes an effort started in FY93 to develop a software system that can be used to accurately predict the performance of the battery cells that are widely used in power systems for satellites and launch vehicles. The resulting system is capable of accurately modeling the performance of nickel hydrogen, nickel cadmium, silver zinc, and lithium ion battery cells. The software system has become widely utilized within the Energy Technology Department of the Electronics Technology Center to both predict and understand battery performance issues. It operates on a desktop PC under Windows 95/98 or NT, and contains all documentation of the theory, approach, and instructions for the use of the system in the standard Windows help format.

At the inception of the project in FY93, a new modeling method that combined fundamental electrochemical principles with a multi-layer finite element technique was developed to allow accurate modeling of the complex physical structures and chemical reactions that occur in battery cells. The next two years of the project were devoted to constructing accurate performance models for the nickel-hydrogen and nickel-cadmium batteries that typically power modern satellites. The performance predictions from the nickel-hydrogen battery model have proven highly accurate, in several situations allowing computer simulations to replace battery test programs for redesigned battery systems. The simulation system was augmented during FY96–97 to allow the performance of silver-zinc batteries commonly used in launch vehicles to be modeled. Further augmentation to the simulation system during FY97–98 has developed the capability to model performance for the emerging lithium-ion battery technology that is now being considered as a possible replacement for the more established battery technologies. The following report describes the simulation methods that have been developed and the validation that has been performed, largely in FY98, for lithium-ion battery cells.

Lithium-ion batteries constitute an emerging technology that has largely been developed for terrestrial commercial applications. Recently, efforts have begun to transition this technology into spacecraft-type batteries. A model capable of accurately predicting how changes in design affect performance and reliability would clearly help develop this technology rapidly for near-term satellite applications.

Lithium-ion battery cells utilize a metal oxide cathode, which provides lithium from $LiCoO_2$, $LiNiO_2$, $LiCo_xNi_yO_2$ or $LiMnO_2$, and an anode that stores lithium in a carbon matrix as Li_xC_6. The carbon matrix consists of a mixture of graphitic, unorganized, and turbostratic carbon phases, with each phase having different activity and voltage characteristics in an electrode. The combination of any of these cathodes with a carbon anode in a wide range of non-aqueous electrolytes provides a lithium-ion battery cell, which has a voltage ranging from 3.6 to 4.0 volts. The development of an approach capable of accurately modeling lithium-ion battery technology must provide a framework that can model the performance of any cathode type, in combination with an anode of arbitrary carbon composition, and utilizing an arbitrary non-aqueous electrolyte. The lithium-ion model developed in this program is indeed capable of simulating the performance of any of these possible combinations of anode, cathode, and electrolyte technology, thus making it of general use to all manufacturers in developing lithium-ion batteries and to all users applying this technology in their power systems.

The lithium metal-oxide cathode was modeled as a 3-dimensional conglomerate of particles imbedded in a conductive matrix, utilizing the multi-layer finite element approach developed for modeling the nickel electrode. For each type of metal oxide cathode four phases, each having a different lithium content and activity, define how the current and voltage depends on state-of-charge. Degradation during life is modeled in the cathode as arising from either electrolyte oxidation or loss of activity from processes such as structural collapse (which can occur if too much lithium is removed from the structure) or proton incorporation. The carbon anode was modeled assuming parallel reactions involving any desired composition of graphitic, unorganized, or turbostratic carbon phases. Each of these phases stores lithium according to established relationships between activity and its voltage or current. Degradation of the anode occurs by plating lithium metal or by trapping lithiated carbon sites by reaction with an electrolyte. Any desired electrolyte can be specified just

by entering its conductivity, viscosity, and activity coefficient data in an appropriate database.

Full validation of the lithium-ion model that has been developed would require extensive electrical and thermal data for all types of lithium-ion cells. This was not possible simply because of limited funding, and because many cell variants were not available. Data obtained from a commercial 0.8 ampere-hour SONY lithium-ion cell was used to validate our model as applied to a cell containing a cobalt oxide cathode and a carbon anode consisting primarily of unorganized carbon. Based on a series of calorimetry measurements, a validated thermal model for this particular type of lithium-ion cell was developed. Figure 1 compares the voltage and heat generation obtained from the computer simulation with laboratory measurements for the SONY cell. The agreement between the simulation results and the measurements is quite good, particularly since the precise composition and physical structure of the electrodes and electrolyte in the SONY cell are not known.

Significant variability in the performance and life of lithium-ion cells can be realized by altering the structures or compositions of the anode, cathode, or electrolyte, as well as the initial state-of-charge of the electrodes. Each manufacturer typically develops his favorite or "optimized" combination of these variables. For example, improved cycle life can often be obtained at the cost of diminished energy density. Figure 2 presents simulation results that show how the use of graphitic carbon can give higher voltage than obtained when predominantly unorganized carbon from coke is used in the anode. However, the highly crystalline graphite typically degrades more quickly as it loses crystallinity during repeated long-term cycling. It is clear from this work that the optimum lithium-ion cell configurations for space applications are unlikely to be close to the designs that are optimized for terrestrial commercial applications.

The software system that has been developed during this program has proven to be a key resource in designing, optimizing, and performing failure analysis of nickel hydrogen, silver zinc, and nickel cadmium battery cells. Continued refinement of the parameters

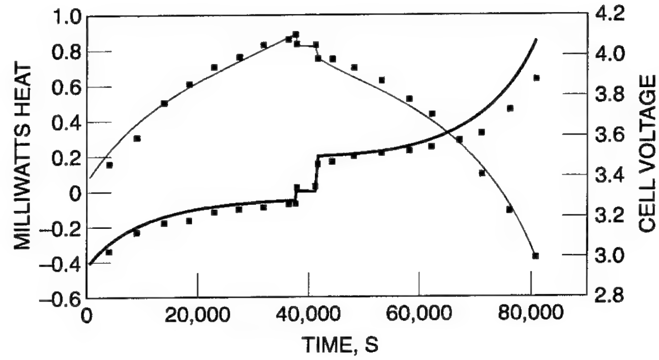

Figure 1. Computer simulation (solid lines) of the performance of a 0.8 ampere-hour lithium-ion battery cell during recharge at 0.08 ampere. The light line is cell voltage and the bold line is cell heat generation calculated by the simulation, while the points show the voltage and heat generation measured for an actual commercial lithium ion cell of the same design as in the simulation.

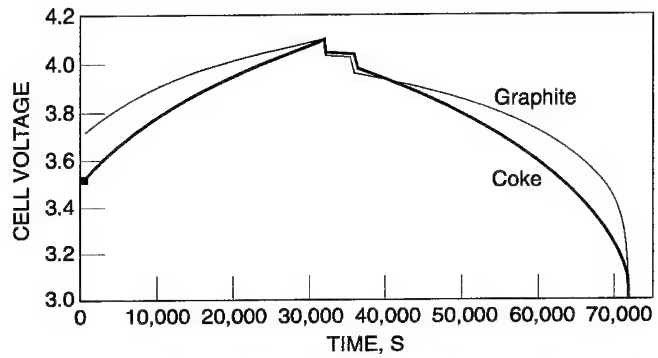

Figure 2. Computer simulation of the differences in charge and discharge voltage for an 0.8 ampere-hour lithium ion cell containing either a highly crystalline graphite carbon anode, or a soft carbon (coke) anode. The charge and discharge rates are 0.08 ampere.

that control the simulations of these cells will occur as better performance and life data are obtained. Similarly, validation and refinement of the lithium-ion model will continue as further data are obtained on different cell designs and the simulation system is applied to the issues facing this emerging technology. It is expected that this simulation resource will be even more critical for transitioning lithium-ion battery technology, whether commercial or aerospace-based, into the space applications of the future.

Virtual Motor for Active Combustion Control

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This report covers the activities of the second year of a three-year IR&D effort in the area of active control of combustion instability. The objective of this project is to demonstrate the feasibility of applying active combustion control to solid rocket motors (SRMs) that experience low-frequency thrust oscillations. A program in active control of combustion instabilities has applications beyond SRMs since gas turbines,

ramjets, and liquid rockets experience similar (and potentially more extreme) thrust oscillations. The emphasis for this year's efforts has been placed primarily on the experimental demonstration of an active control scheme for an SRM. Following is a brief summary of background material and a description of the principal accomplishments for FY98.

Solid rocket motors used on launch vehicles are susceptible to pressure fluctuations that occur at the natural acoustic frequencies of the combustion chamber. The cause for one particular form of low-frequency instability is the coincidence of a periodic fluid mechanic phenomenon within the combustion zone (vortex shedding) with a natural longitudinal chamber frequency [1, 2]. The result is organized pressure oscillations, which are manifest as thrust oscillations and vehicle vibrations. The resonant pressure fluctuation amounts to approximately 1 percent of the total chamber pressure, the frequency of which varies with time as the propellant burns away and the internal geometry changes. Solid rocket motors on the Space Shuttle, Taurus, and Ariane 5, for example, have all experienced low-frequency (<100 Hz), ordered pressure oscillations, and their respective organizations have expressed interest in techniques that could eliminate these oscillations.

Adaptive, active control of such disturbances, using timed injection of a small amount of monopropellant at the motor head end to control the oscillation, is an attractive alternative to passive damping techniques. At present, passive control involves a fix that focuses on externally damping the aftereffects of the combustion-zone fluctuations (i.e., the vibrations) without eliminating their source. Active control, on the other hand, attacks the chamber pressure oscillations directly by perturbing the combustion and fluid mechanic processes that cause the phenomenon. An adaptive scheme is ultimately required because the oscillations vary in frequency and amplitude as a function of time and from motor to motor.

Active control of combustion instability is a relatively new field; work in this area has been spurred in recent years by advances in high-frequency injectors and signal processing [3]. Current activity is limited to fundamental research at Cal Tech, Georgia Tech, Physical Sciences Inc., NRL (China Lake), Stanford, and the Centre National de la Recherche Scientifique (CNRS). A competitive position by Aerospace in this emerging field will place the corporation at the forefront of this much-needed propulsion technology. Additionally, no organization besides Aerospace has or is currently doing active control of the specific type of low-frequency SRM instability described above.

Fortunately, vortex-driven instability in an SRM is based on a phenomenon that can be reproduced in a cold-flow facility, making the development of corresponding control schemes much easier and less expensive than analogous development on a hot-fire engine. Therefore, the goal of this past year was to demonstrate ordered pressure oscillations within a simple cold-flow SRM model and initiate the evolution of a simple yet robust active control scheme to suppress them.

Four primary goals were accomplished during this second year of the project: (1) a literature search was conducted; (2) ordered pressure oscillations were demonstrated in the laboratory; (3) a new experimental apparatus was designed, fabricated, and installed; and (4) initial secondary injection work was performed. Each of these tasks is described in the following paragraphs.

A review of relevant research papers and technical reports was performed. The ongoing literature search has, to date, uncovered nearly 100 works dealing with topics ranging from the basic physics of the acoustic/vortex feedback mechanism to fundamental combustion instability and its active control. Some of the findings proved valuable in identifying the proper cold-flow experiment in which to reproduce the fluid-mechanic/acoustic feedback mechanism (see below). In addition, the current state of the art in experimental active control research was surveyed. In general, the technology is still quite young, and most experiments have demonstrated only open-loop control at a fixed frequency or closed-loop control utilizing simple feedback schemes. While the theories on combustion instability and active control are quite advanced, few adaptive control schemes have been applied to an experimental situation.

One of the primary accomplishments in the laboratory was the demonstration of fixed-frequency pressure oscillations near an acoustic mode of the model chamber. The typical geometry of an SRM chamber was modeled by a simple cylindrical tube with an internal airflow representing the flow of combustion gases. By placing two orifice plates within the tube, a mechanism for the generation of periodic flow disturbances (i.e., vortices) was established. Figure 1 shows a schematic of the basic experimental setup. The orifice plates simulate actual protrusions and cavities that are associated with either the joints or internal grain geometry of an SRM. On the cold-flow experiment, the position and size of the orifice plates determines the natural frequency of the flow disturbance; when this natural frequency is near an acoustic mode of the tube, resonance occurs in the form of ordered pressure oscillations. A successful experimental result is displayed in Figure 2, which illustrates a case with a quarter-wave oscillation frequency near 100 Hz.

Demonstration of Figure 2 results in the laboratory was a primary milestone of this project because ordered pressure oscillations are needed before an active control scheme to eliminate them can be developed. Previous

researchers have shown that the production of such oscillations, although commonly seen in solid rocket firings, is often difficult in cold-flow laboratory simulations [4, 5]. Upon demonstration of the oscillations using the simplified setup, experimental efforts concentrated on designing and building an improved, intermediate-scale rig. The new Plexiglas flow chamber was made optically accessible to study the interaction between the active control process and the internal flow physics using state-of-the-art laser diagnostics. Shake down and characterization of the new facility is presently underway.

In conjunction with the fabrication of the new experimental model, preliminary work on the active control technique was performed. This work included the selection of a fast-response injector to deliver the pulsating secondary fluid (see Figure 1). While current fiscal year funds did not allow the purchase of the ideal secondary-gas injector, a subscale interim version was acquired to test some first-order concepts. To support the secondary injection experiments, an analytical model of the time-dependent process was developed; this model aided the design of the new rig mentioned above and will be utilized to guide the purchase of a better injector in FY99.

Figure 1 shows the basic control scheme currently under investigation. This scheme will use the measured pressure within the flow model as the feedback signal to the injector controller. The frequency, amplitude, and phasing of the injection flow rate will be adjusted to precisely counter the pressure oscillations. The secondary flow rate required to suppress the oscillations is expected to be less than 10 percent of the total air (i.e., propellant) flow rate.

An evolutionary approach to achieving adaptive, active control has been selected for the FY99 phase of the experiment. The general sequence will be as follows: (1) demonstrate open-loop control at a fixed frequency and amplitude; (2) demonstrate closed-loop

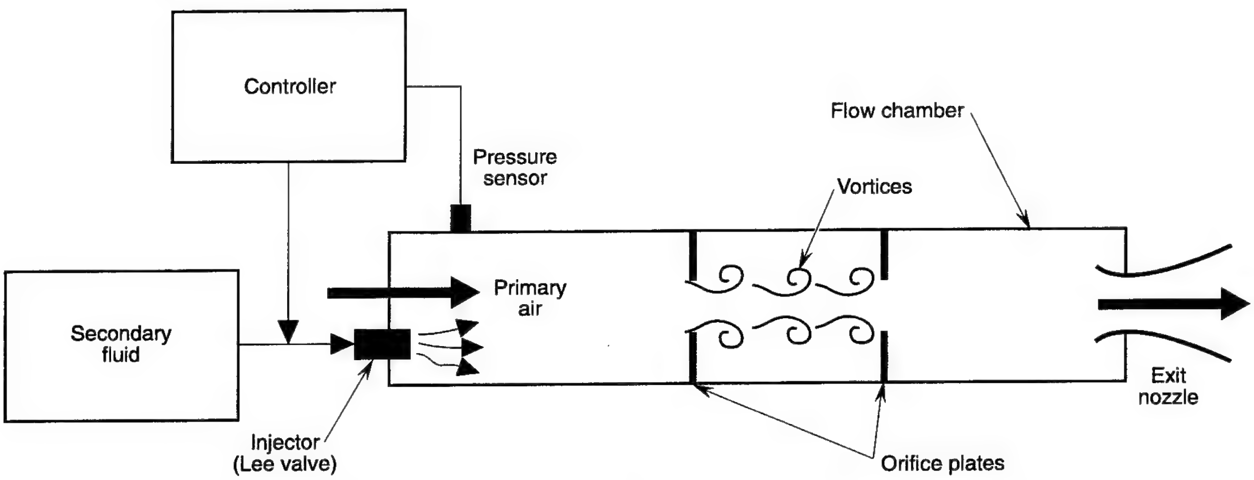

Figure 1. Schematic of the experimental active control apparatus. The flow tube simulates the internal geometry of a SRM, and the orifice plates simulate the internal flow disturbances from which periodic vortices are shed. The active control scheme will employ pulsed secondary injection at the front end using a simple control loop with chamber pressure as the feedback signal.

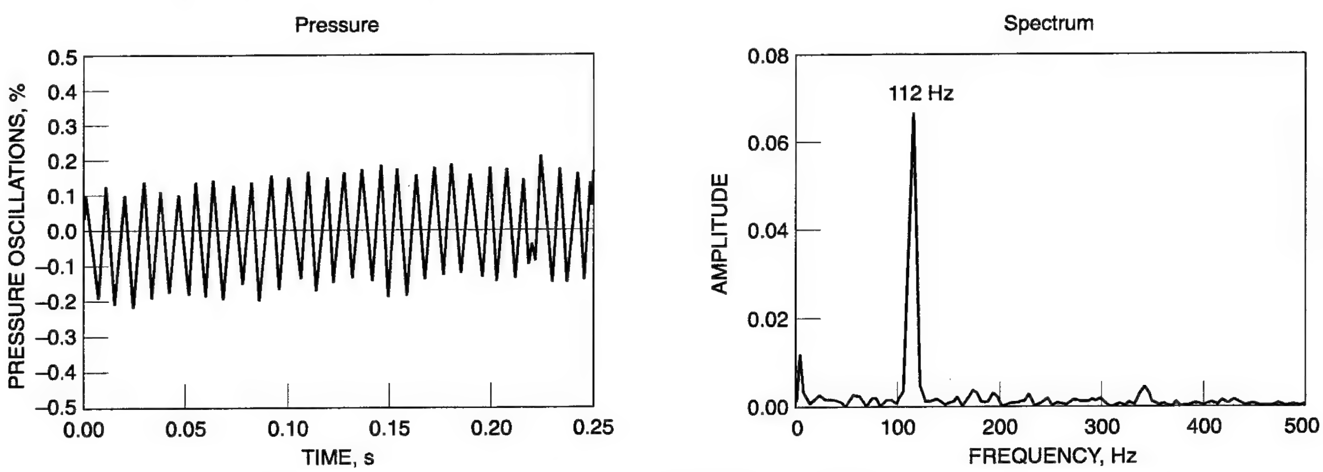

Figure 2. Sample experimental results showing the magnitude and frequency of the pressure oscillations within the cold-flow experimental setup shown in Figure 1. The object of the active control scheme is to suppress this (or similar) ordered oscillation.

control at a fixed frequency and amplitude; (3) demonstrate a time-dependent oscillation frequency and amplitude within the flow chamber via a variable-area exit nozzle; and (4) demonstrate adaptive, active control of the time-dependent oscillations. Complicated control schemes are unnecessary at this time, given the current status of applied active combustion-control technology and the current level of funding.

Additional tasks during this fiscal year included the presentation of a work-in-progress poster at the 27 International Combustion Symposium, and submittal of a paper describing the experimental effort to the January 1999 AIAA Aerospace Sciences Meeting

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Advanced Aeroelastic Analysis for Flexible Launch Vehicles

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The objective of this project is to develop a computational method that is capable of analyzing the nonlinear, dynamic aeroelastic behavior of a flight vehicle. This project will provide Aerospace with a new capability to assess the impact of aeroelastic coupling on the dynamic response of launch vehicles and the ability to evaluate the next generation of medium/heavy lift launch vehicles. This report covers activities during the second year of the project. It presents the computational method used, results of validation, and plans for future efforts.

The study of aeroelasticity for a flight vehicle involves significant interactions among aerodynamic and elastic forces. The aerodynamic forces acting on a vehicle depend on its body shape with respect to flow, which in turn depends on the flexibility of the vehicle. Therefore, to solve an aeroelastic problem, the structural equations of motion must be simultaneously integrated in time with the unsteady aerodynamics. In the current project, a computational method for computing unsteady flows and aeroelastic responses of a flexible body has been developed. The equations governing the nonlinear aerodynamics and structural aeroelastic system are simultaneously integrated in time in a fully coupled manner. The aerodynamic governing equations are the unsteady compressible Navier-Stokes equations written in strong conservation form. The solution algorithm for the flow solver is based on a total variation diminishing (TVD) technique. The TVD methodology is able to resolve complicated wave development and interaction, which is frequently encountered by the launch vehicles in the transonic regime.

To solve the governing aeroelastic equation of motion of a flexible body, we adopted a modal approach in our analysis. With this approach, aeroelastic displacements at any time are expressed as a function of a finite set of assumed modes, and the deformation of the continuous structure is represented by deflections at a set of discrete points. The modal aeroelastic equation of motion is solved by a numerical technique based on the linear acceleration method. The deformation of the body, in turn, is specified by the displacements determined from the integration of structural equations. In the time-marching aeroelastic calculation, the computational mesh must then be updated at each timestep to conform to the aeroelastically-deformed shape of the body. The strategy for updating the mesh points is to model the computational mesh as a network of springs and solve the static equilibrium equations for the network. This dynamic mesh algorithm allows the mesh to be deformed for arbitrary deflection and still maintains the mesh quality near the body. The pressure distributions on the deformed body are recalculated by the flow solver and subsequently integrated to give the generalized aerodynamic forces for solving the structural equations of motion at a new time.

Steady and unsteady computations were made to validate the accuracy and to demonstrate the capability of the recently-developed flow solver. Steady-state calculations were performed for a NACA 0012 airfoil, a

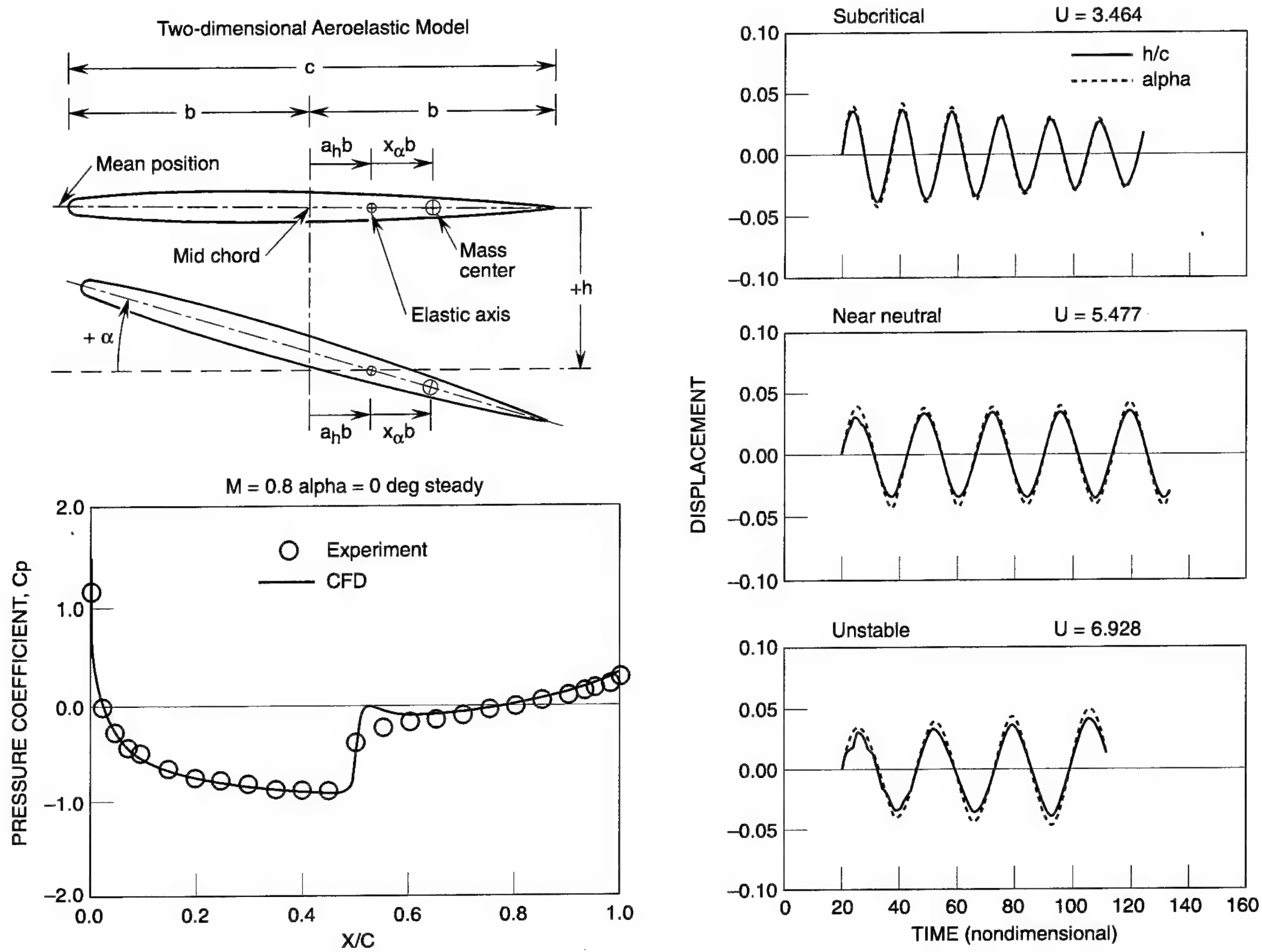

Figure 1. Transient Flutter Analysis of NACA 0012 Airfoil at $M_\infty = 0.80$, $\alpha 0 = 0.0$ deg.

wing, and the payload fairings of two existing launch vehicles in the transonic regime. A two-dimensional unsteady flow computation and the transient flutter analysis of a NACA 0012 airfoil were made to validate the time-marching approach of the aeroelastic calculation. Unsteady flow analysis was performed for the airfoil pitching harmonically about the quarter chord with amplitude of 2.51 degrees and a reduced frequency based on a semichord of 0.0814 at a free stream Mach number of 0.755. The instantaneous chordwise pressure distributions at eight time instants of the oscillating cycle compare well with experimental data. Good agreement of the numerical results with experimental data demonstrates the ability of the computational method to correctly calculate the amplitude and phase of the unsteady pressures, which are essential in aeroelastic calculation.

A flutter analysis was performed for the airfoil with two degree-of-freedom pitching and plunging motions. The aeroelastic computations were performed for three different nondimensional free steam velocities, U = 3.464, 5.477, and 6.928, and at $M_\infty = 0.80$, which correspond to subcritical, near neutrally stable, and unstable aeroelastic responses. The initial condition for the flow was taken as steady flow over the airfoil at zero angle of attack. A plunging velocity of 0.03 was introduced to initiate a vibration in the system. The steady results and the time responses of the plunging and pitching displacements (h/c and α) are shown in Figure 1.

The computational method was also applied to the aeroelastic response of the payload fairing (PLF) of an existing launch vehicle in transonic flow. The structural properties of the PLF were modeled using three modes whose modal shapes are shown in Figure 2. The time-marching aeroelastic computations were made at a dynamic pressure of 500 psf and $M_\infty = 0.80$. An initial modal velocity was introduced in all three modes to initiate a vibration of the system. Preliminary aeroelastic time responses using Navier-Stokes aerodynamics are also shown in Figure 2. The PLF response is seen to be dominated by the first mode, and the motion is decaying, implying that the PLF is stable at q = 500 psf.

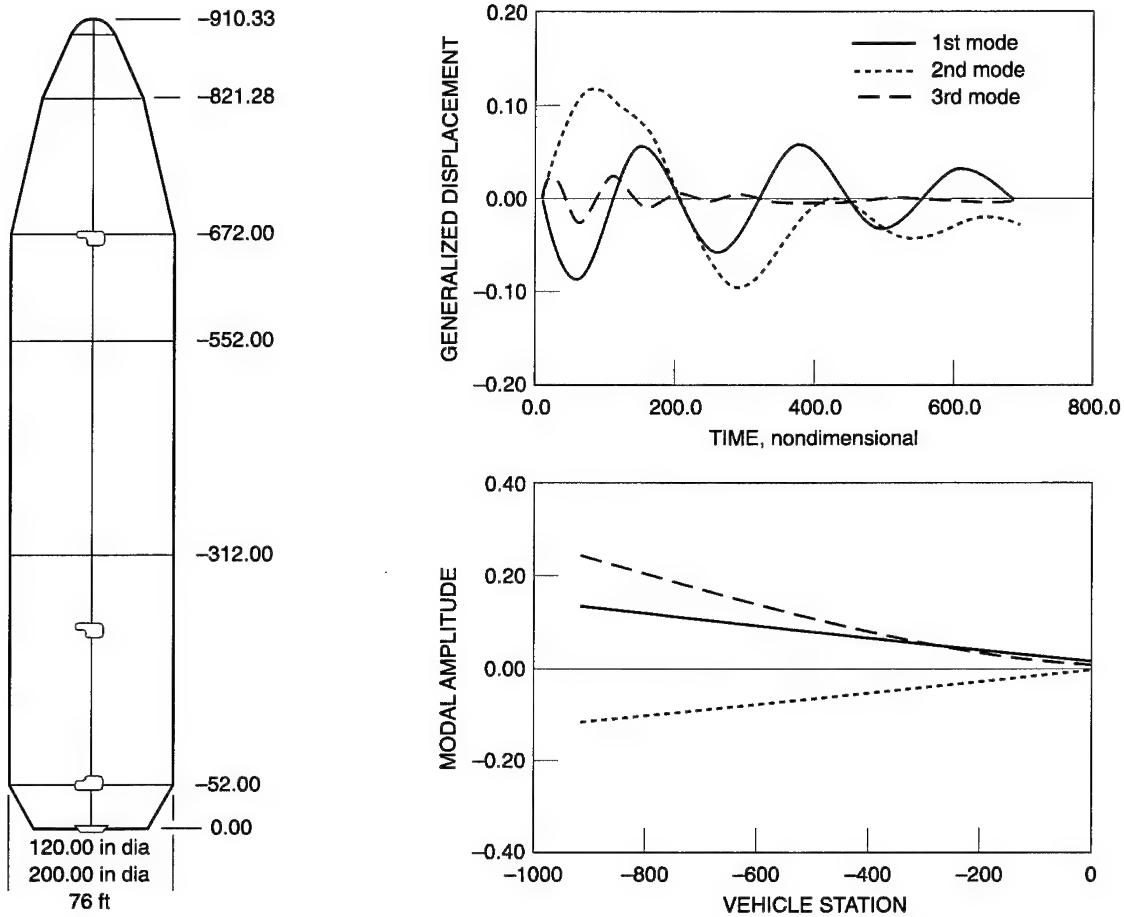

Figure 2. Aeroelastic Analysis of A Payload Fairing at $M_\infty = 0.80$, $\alpha 0 = 0.0$ deg.

In summary, the project is progressing according to the technical objective set out in the FY98 plan. A numerical procedure for computing the unsteady flows and aeroelastic responses of a flexible body with an adaptive dynamic mesh has been developed. Steady and unsteady computations were made to validate the accuracy and to demonstrate applications of the flow solver. Transient flutter analysis of an airfoil was performed to validate the time-marching approach of the aeroelastic calculation. The computational method was applied to investigate the aeroelastic response of the PLF of an existing launch vehicle in transonic flow. Future work will further develop the method for computing cases involving multi-bodies, and improve computational accuracy and efficiency.

Nondestructive Evaluation of Composite Materials

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The focus of this investigation is on the development of techniques for detecting, characterizing, and quantifying damage in fiber-reinforced composite materials. Fiber-reinforced composite materials are widely used within the aerospace industry. Their high strength-to-weight ratio and ability to be tailored for specific applications make them attractive for a host of applications including solid rocket motors (Titan IV SRMU, Delta GEMs, IUS, Pegasus, Taurus), launch vehicle fairings (Delta), composite overwrapped pressure vessels, honeycomb panels and satellite structural members. Unfortunately, fiber-reinforced composites are, in general, more difficult to inspect than their metallic counterparts. These difficulties are compounded by the impact sensitivity of the graphite/epoxy composites used in a majority of aerospace composite structures. Studies have shown graphite/epoxy composites to be susceptible to impact damage that may leave no obvious visible surface indications, yet degrade the performance of the structure. Material performance is highly dependent

upon fiber integrity—break the fibers and the materials fail under reduced load. Standard nondestructive evaluation (NDE) techniques cannot resolve fiber breaks unless the damage is obviously severe. Consequently, inspectors look for damage that typically, but not always, accompanies fiber breaks—such as ply delamination and surface impact indications. There are three tasks in this investigation, each addressing a different aspect of impact damage to composite materials: (1) damage evaluation, (2) damage detection, and (3) health monitoring. The first task involves the direct detection and evaluation of fiber damage (breakage). This requires the development of an appropriate NDE technique (flash thermography, eddy currents, and high frequency ultrasound) sensitive to the characteristics of fiber damage. The second task is to develop a calibrated indicator paint that would indicate the location and level of a particular damage event. The indicator paint is a natural complement to the fiber damage/evaluation task. Impacts identified using the indicator paint could then be dispositioned using a meaningful measure of composite damage (fiber breakage). The third task is to develop a micromechanical embedded strain gage for monitoring the effective load capacity of a structure. Using this system internal structural loads can be monitored during service using a wireless data acquisition system. The addition of the embedded strain gage will be an additional complement to the other investigation tasks, minimizing inspection downtime and insuring that the structure behaves as expected. During FY98 progress was made in each of these tasks.

Initial work was undertaken to evaluate the flash thermographic approach to detecting fiber damage. Flash infrared (IR) thermography is a well-documented NDE technique for many of the composite structures used in aerospace applications. However, it has not been specifically applied to the detection of fiber damage. The advantages of flash thermography include: (1) non-contacting/remote inspection capability, (2) a wide field of view, (3) fast inspection times, and (4) easily archived data. The disadvantages associated with thermography include relatively high equipment costs and sensitivity to variations in surface emissivity that can mask flaw indications.

A basic flash thermographic inspection consists of two distinct steps. The first is to generate a uniform thermal gradient through the structure using a short (<30 ms) heat flash from photographic-type flash units; the second is to capture the surface temperature map as the structure returns to thermal equilibrium. Changes in conductivity such as that caused by fiber breakage will result in localized deviations in the surface temperature. An initial experiment was performed using an impacted section of a composite rocket motor case. A case section was subjected to a severe impact (250 ft-lbs). After ultrasonically mapping out the damage area, a flash thermography inspection was done in an attempt to evaluate the fiber damage. The results did not clearly indicate damaged fiber, but rather the underlying delaminations. This suggests that the impact used to create the damage was too severe, in that the signal from the accompanying delamination swamped that of the broken fibers. In future work, a new sample with a less severe impact site will be subjected to the same tests.

The second task was to develop an impact detection system utilizing a paint loaded with dye-filled microballoons as an impact indicator. When a structure coated with the indicator paint is impacted the microballoons will break, releasing the dye and marking the surface of the structure. The dye marking will provide for a more reliable field inspection of the component, highlighting the areas requiring additional inspection. To be effective, the breaking strength of these spheres must be adjusted so that only those impacts that exceed normal handling loads will result in leakage of the dye. In FY98 we began work with a microballoon manufacturer to develop microballoons filled with a fluorescent liquid with the proper fracture strength. This effort, in combination with impact sensitivity experiments at Aerospace, resulted in the production of several iterations of indicator paint using different carrier materials and microballoon sizes. The current version of the marker material consists of dye-filled microballoons suspended in a white paint that can be applied as either a primer or an over-coating. Ongoing calibration experiments are using a graphite/epoxy panel coated with the microballoon mixture. The test matrix includes: (1) calibration of the coating based on a known impact to the composite surface, and (2) evaluation of different application procedures for the indicator paint.

The third task was directed toward the development of submillimeter strain gages that can be embedded in composite structures during manufacture. Such devices could be used to determine how a structure carries a load or to detect strains associated with fiber breakage. To be practical, such micromechanical devices would need to be wireless, requiring the development of wireless techniques for powering and reading the gages. To meet this requirement, a technique was conceived at Aerospace to use ultrasound to transmit both power and information. With this technique, a sensor embedded in a structural composite contains a piezoelectric transducer. When a strain reading is desired, an external transducer generates an acoustic wave at the resonant frequency of the embedded transducer and directs it through the structure to excite oscillations in the embedded transducer. The oscillations in the transducer produce an AC electric current at the frequency of the acoustic wave. This current is then rectified and voltage-

regulated to produce the DC voltage necessary to power the strain sensor and associated electronics. The strain reading is then converted into an encoded acoustic wave that is sent out by the embedded transducer and received by the external transducer.

Clearly, this method requires development in several areas including acoustic power transmission, high frequency rectification, and low power sensor systems. The goal for the first fiscal year was to demonstrate the production of useful power using acoustic waves. Several links in the process were demonstrated this year. Acoustic power transmission was demonstrated using paired 1-MHz piezoelectric transducers in water at a separation of 23 cm. Using a resistive load, the effective AC power received was in excess of 10 mW. In addition, a high frequency rectifier circuit was designed and tested, and shown to be satisfactory for low power, high frequency operation. Finally, several commercially-available low power voltage regulators were obtained and tested. These are the principal components of an acoustic power transmission system, and will be combined early in the next fiscal year.

The overall goal of this task is to demonstrate an acoustically-powered strain sensor. During the first year, we have demonstrated the basics of acoustic power transmission. During the next year, we anticipate refining that capability by exploring different transducer types and frequency ranges. We also expect to evaluate low power strain sensors, and build a working prototype acoustic powered strain sensor. In the third year, we expect to design a smart acoustic powered sensor with acoustic communication of the strain measurement.

The goal of this IR&D program is to develop new NDE tools appropriate for use in graphite/epoxy composite structures. The successful completion of this work has the potential to dramatically impact how composite materials are used in service applications, providing a field inspection capability that is not currently available to the industry.

Advanced Tribological Materials for Spacecraft

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The overall goal of this IR&D program is to extend the life of spacecraft mechanisms through successfully incorporating hard coatings on moving mechanical components. The main objectives of this program are (1) to optimize the performance of hard coatings such as titanium carbide (*TiC*), deposited on bearing surfaces at low temperatures, (2) to address lubrication of hard coatings by studying the chemical interactions of lubricant and additive model molecules with clean, well-characterized *TiC*, vanadium carbide (*VC*), and titanium nitride (*TiN*) surfaces, and (3) to study atomic scale tribology on surfaces of crystals and films in an ongoing collaboration with the University of Houston (UH).

To better understand the tribological properties and performance of hard coatings in moving mechanical assemblies, hard coatings were deposited in-house using a pulsed laser deposition (PLD) capability. The main attribute of this deposition capability is its ability to deposit high quality hard coatings at room temperature. Low deposition temperatures are quite critical for tribological applications involving precision-bearing steels, as these substrates can lose some of their important properties, such as hardness, when exposed to temperatures exceeding 650 K.

For our applications, the conventional PLD process was modified to eliminate undesired particles from being co-deposited with the film. This special process, invented in this IR&D program, was the subject of a patent application. The improvements resulting from this modified PLD process are evident in the coating morphology, shown in Figure 1. Use of the modified PLD process resulted in greatly improved tribological properties of our *TiC* films. In particular, modified thrust bearing components coated in this program with PLD-*TiC* have surpassed the performance of uncoated all-steel bearings by more than a factor of 100 when tested in our vacuum wear-tester under identical conditions of load and operating velocity. While more tests are needed for a statistical sampling of coating performance, our initial results show that *TiC* coatings, deposited using the special PLD process developed at Aerospace, have remarkably improved the performance of steel bearings. These results lend strong support to continued investigations on the deposition and properties of wear-resistant hard coatings.

TiC films have been successfully deposited on two different types of bearing steels, namely 52100 and 440C steels. Our work is the first report of a successful low-temperature deposition of *TiC* on 52100 steel. More recently, progress has been made in depositing *TiC* at room temperature on REX20 steel, a high fatigue-strength tool steel. Depositions on REX20 offer a direct comparison to commercial *TiC* coatings deposited on this steel using a high-temperature (1200 K) chemical vapor deposition process [1]. To help optimize the tribological performance of these films, fundamental film properties were studied using a

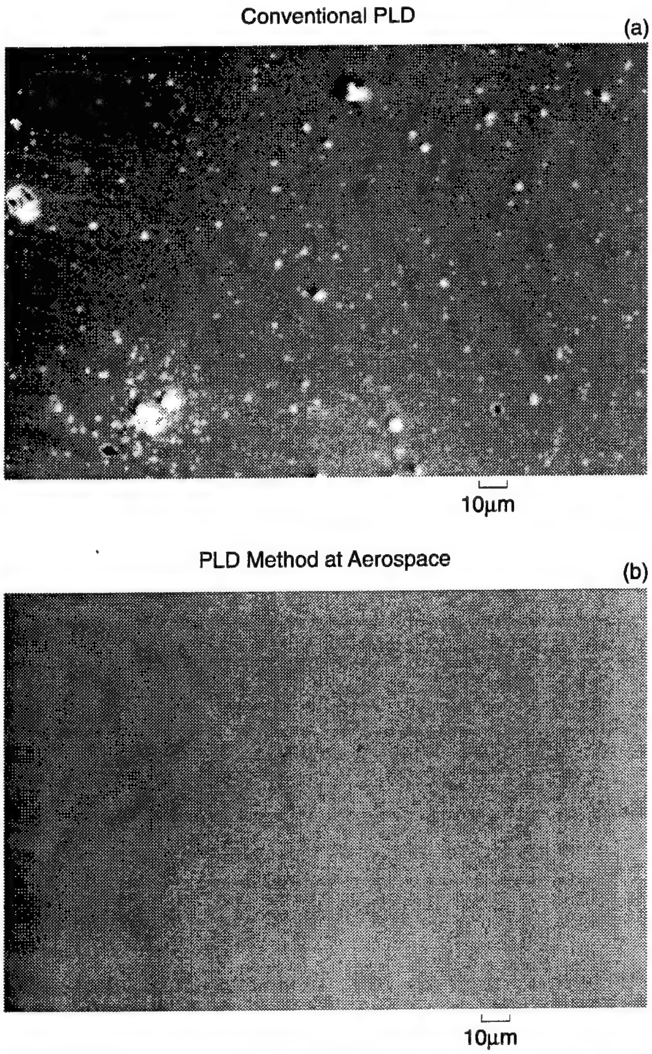

Figure 1. Surface morphology of a TiC film deposited on a 52100 steel substrate as seen in scanning electron microscopy: (a) using conventional Pulsed Laser Deposition (PLD) and (b) using the modified PLD process developed in this IR&D program.

variety of analytical techniques such as scanning electron microscopy (SEM), atomic force microscopy (AFM), X-ray photoelectron spectroscopy (XPS), X-ray diffraction, and transmission electron microscopy (TEM).

The deposited *TiC* films were very smooth and essentially particle-free over the entire area of the substrate. The SEM photographs in Figure 1 illustrate the dramatic reduction in particle density on the surface of a *TiC* film deposited on a steel substrate resulting from the modified PLD process developed in this program. A low particle density is critical for wear-resistant applications of hard coatings involving ball bearings. This is because the surface finish of bearings is on the order of 0.1 mm, and hard particles, if present, can damage the bearing surfaces and induce wear on the surfaces. An AFM image of the as-grown *TiC* film provided a quantitative assessment of the surface roughness. The average and RMS surface roughness values of *TiC* on a 52100 substrate, corresponding to a surface area of 112 mm^2, were 1.2 nm and 1.6 nm respectively. These numbers imply that the surface smoothness of the deposited *TiC* film is better than optical quality. XPS data acquired on the as-grown samples revealed *Ti*, *C*, and *O* as the components of these films. The oxygen was present as a surface titanium oxide that was removed upon sputter-etching the film. The oxide layer was ~5 nm thick and is typically observed in all *TiC* films that have been exposed to air. The *C*/*Ti* ratio of 0.9, after sputtering, is consistent with the formation of *TiC*, which is typically sub-stoichiometric in *C* [2], with some potential preferential sputtering of *C* relative to *Ti*.

An important feature of our PLD-*TiC* films is that they consist of extremely small crystallites, which is generally viewed as being beneficial to both the adhesion and hardness of the films. The crystallite size of PLD-*TiC* from both the *TiC*/52100 and *TiC*/440*C* X-ray diffraction scans was estimated to be ~7.5 nm. This value was found to be consistent with the range of 3–17 nm directly measured from dark-field TEM. From the selected area electron diffraction patterns for *TiC*/52100 and *TiC*/440*C* films, excellent correlations were found between the observed d-spacings and reference values for *TiC*, confirming that the deposited films were indeed *TiC*.

In-situ spectroscopic investigations of the PLD plume from which the *TiC* coatings are deposited have been initiated using a state of the art charge-coupled-device (CCD) sensor, gateable to 5 ns. Our investigations have identified optical emission from both titanium neutrals and titanium ions in the laser ablation plume. Measurements of time-resolved emission from these species in the ablated plume are currently in progress. A correlation between species identified in the laser-ablated plume during deposition and macroscopic tribological film properties is being sought to aid the optimization of film growth and performance.

To evaluate and optimize the performance of hard coatings, and to select appropriate lubricants for space-related applications, it is essential to understand the coatings' chemical interactions with lubricants, additives, and environmental materials. Using spectroscopic techniques, which include XPS and high-resolution electron energy loss spectroscopy (HREELS), we have examined single crystal surfaces of hard materials (*TiC* and *VC*) after exposure to adsorbates that were intended to model the constituents of common lubricants. We have focused on oxygen-containing molecules, as the active site in the molecular structure of many lubricant additives is an oxygen atom. Our fundamental studies on the surface chemistry of hard materials have been complemented by valuable tribological information on the friction and wear of these materials gained through our collaboration with UH. The results will allow us to

draw relationships between the surface chemistry and tribological performance of hard materials and thus make intelligent decisions on the choice of lubricants and additives for these systems.

Studies of the chemical interaction of water with *TiC* and *VC* have been completed. This work showed that while the surfaces of *TiC* and *VC* have similar reaction products, the *TiC*(100) surface is more reactive with respect to the decomposition of water. Work has continued with the study of carbon monoxide (*CO*) and methanol (CH_3OH). Our studies show that *CO* bonds strongly with *VC* and weakly with *TiC*. These results are in accordance with predictions based on our understanding of surface electronic structure. The chemistry of CH_3OH on these surfaces is intriguing. While both *TiC* and *VC* form surface methoxy groups, the *VC* surface is capable of breaking *C-H* bonds, which might be very important in understanding hydrocarbon lubricant decomposition. We are currently extending our investigations of adsorbates on single crystal *TiC* to the same adsorbates on thin films of PLD-deposited *TiC*. These studies will help us understand the chemistry of model lubricant molecules on hard coatings, which is of practical importance, and provide valuable comparisons to "ideal" single-crystal hard materials.

Our collaboration with UH has resulted in valuable information regarding the differences in friction between single crystal *TiC*, *VC*, and *TiN* in nitrogen atmosphere with varying relative humidity. The AFM was used for measuring the friction between various counter-surfaces and the effect of adsorption of small molecules. These measurements showed that the friction between *TiC* surfaces was the lowest. For this study, silicon nitride AFM tips were coated with *TiC*, using the low-temperature PLD process, and also with thin films of other materials.

Significant strides have been made in our program toward the development of high-quality hard coatings and a fundamental understanding of the surface chemistry and tribological performance of hard materials. The PLD process developed at Aerospace has resulted in coatings with excellent surface morphologies, thus overcoming a major impediment to the commercialization of PLD for numerous applications. Our work is the first report of a successful low-temperature deposition of *TiC* on 52100 steel. We are continuing to develop our understanding of critical deposition parameters and film properties that will make PLD a viable method for high-performance tribological coatings. In parallel, our studies on the surface chemistry of hard materials have addressed fundamental issues regarding the reactivity of these materials, paving the way for intelligent decisions on the choice of lubricants and additives. Our surface chemistry studies are being extended from ideal, single-crystal hard materials to PLD coatings of these materials developed in this program. The combined efforts of coating development, testing, surface chemistry, and tribology that are included in this program will provide a comprehensive picture of the performance of hard coatings and their ability to minimize wear and extend the life of mechanical components. This in turn will offer a firm basis for the successful implementation of hard coatings in spacecraft components.

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Advanced SEU Test Facility

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This report summarizes a one-year IR&D project during which we improved our single event upset (SEU) test facility and demonstrated its effectiveness for SEU testing. The SEU test facility at the Lawrence Berkeley Laboratory (LBL) 88-inch cyclotron was used to measure sensitivities of various microcircuits to heavy ions. Recent improvements in the motion control, the beam diagnostic, and the test device interrogation subsystems have made it possible to measure SEU susceptibility of microcircuits more accurately and rapidly. SEU test facilities—such as the one at the LBL cyclotron—provide heavy ions of low to intermediate energies. These ions collectively possess linear energy transfer (LET) values ranging from a fraction to about 100 MeV/(mg/cm^2). Over the years we have assumed that SEU sensitivities depend on LET values of ions only. However, recently other issues have been raised concerning the differences between the effects of higher energy ions and those of low energy ions.

The ion track structure plays an important role in the generation of charge in semiconductor material [1,2]. The generated charge, which in turn affects charge collection, is influenced by the ion energy as well as the

LET [1,2]. In some cases it has been suggested that the concept of LET needs to be reconsidered [3].

Recent articles have shown that high energy ions, when compared with lower energy ions having the same LET value, may provide a larger distribution of generated charge, and thus a larger upset cross-section [1]. Contrary to this purported mechanism, other observations have been made in which lower energy ions in some instances can cause upsets, while higher energy ions with the same LET do not [4,5].

Charge collection is a complex phenomenon affected by the size of sensitive regions and the structural arrangements of multiple junctions. Therefore, it is controlled not only by the energy of ions but also by the geometric arrangement of junctions and the properties of the semiconductor material [2,3,6,7].

We have tried to observe these effects, which result in SEU, on a macroscopic scale. For that purpose, we have compared SEU test results of two static random access memory (SRAM) device types obtained at different accelerator sites, where ions of varying energies are available. For this study test results acquired within the last year are combined with those obtained earlier. The test device types are MICRON MT5C1008 128K×8 SRAM and IDT71256 32k×8 SRAM. These devices are not new microcircuits, since their lot date codes are DC9322 and DC9210 for MT5C1008 and IDT71256 types, respectively. However, some of them are currently utilized in space; consequently, SEU studies with these device types have been continuing.

We have used several accelerators of varying capacity in order to utilize ions with a wide range of energy. The selected ion species are shown in Table 1. The energy of ions tends to increase as we go down the list of facilities in Table 1. Even though some facilities (such as the LBL Bevalac and TASCC described below) are no longer in use, our test data were taken while all these facilities were fully operational. A brief description of the test facilities follows.

Table 1. List of sample ions utilized for SEU testing at various accelerator facilities.

Facility	Ion	Total (MeV)	Kinetic Energy Per Nucleon (MeV/nucl.)	LET [MeV/ (mg/cm^2)]	Range in Si (μm)
LBL 88" cycl.	^{16}O	428	27	0.9	1,100
	^{40}Ar	180	4.5	15	46
	^{136}Xe	600	4.4	63	50
	^{209}Bi	950	4.5	95	50
TASCC	^{58}Ni	1,900	34.5	9.9	560
	^{127}I	1,600	12.5	49	140
	^{197}Au	1,707	8.7	91	80
NSCL	^{12}C	720	60	0.3	5,510
	^{40}Ar	2,110	53	2.5	1,860
	^{84}Kr	4,850	58	10	1,180
GANIL	^{132}Xe	4,084	30.1	34	380
	^{132}Xe	2,090	15.8	47	160
LBL Bevalac	^{28}Si	3,100	282	0.6	4,500
	^{56}Fe	23,000	410	1.7	38,000
BNL AGS	^{197}Au	1,600,000	11,400	12.5	~400,000

The LBL 88-inch cyclotron in California is capable of providing a copious flux of low and intermediate energy ions for a wide range of LET values [8]. The Chalk River Laboratories' Tandem Accelerator Super-Conducting Cyclotron (TASCC) in Canada, the cyclotron at the National Superconducting Cyclotron Laboratory (NSCL) located on the campus of Michigan State University, and the Grand Accelerateur National d'Ions Lourds (GANIL) in France are relatively similar in their acceleration capability [9,10,11]. At these facilities, the typical ion energy can extend to tens of MeV/nucleon. The SEU irradiation facility at TASCC had been operational for general SEU study before it was closed down [9]. The NSCL cyclotron has been used by several groups for SEU investigations in recent months. The LBL Bevalac in California and the Brookhaven National Laboratory's Alternating Gradient Synchrotron (BNL AGS) in New York are one step above the previously-mentioned facilities in their ability to deliver higher energy ions [3,12,13,14]. They can accelerate ions to thousands of MeV/nucleon. Unfortunately, the LBL Bevalac is no longer operational. One disadvantage associated with the use of these facilities is that there are various safety issues to consider while carrying out experiments. However, the major advantage is that ions can penetrate a long range and they indeed possess the properties of cosmic rays.

The test results obtained with the Bevalac beam for IDT32k×8 SRAMs are superimposed on the cross-sections taken with the lower energy ions at the LBL 88-inch cyclotron as shown in Figure 1. The error bar associated with the Bevalac data is caused by the uncertainty involved in the particle counter. The test results for the 128k×8 SRAM obtained at GANIL, TASCC, and BNL AGS are superimposed on the cross-section curve obtained at the LBL 88-inch facility, as shown in Figure 2. All results were obtained with incident ions normal to the device surface. The data point obtained at GANIL lies slightly lower than those taken at the LBL 88-inch facility, while the data taken at TASCC are at the same level as those collected at LBL. The AGS results show that the cross-section is comparable to those results obtained at the LBL 88-inch facility. The error bar associated with the BNL AGS data point is caused by an uncertainty in the particle counter.

Investigations of ion-induced charge collection for relatively simple structures, such as a PN diode, have shown that ions of higher energy with

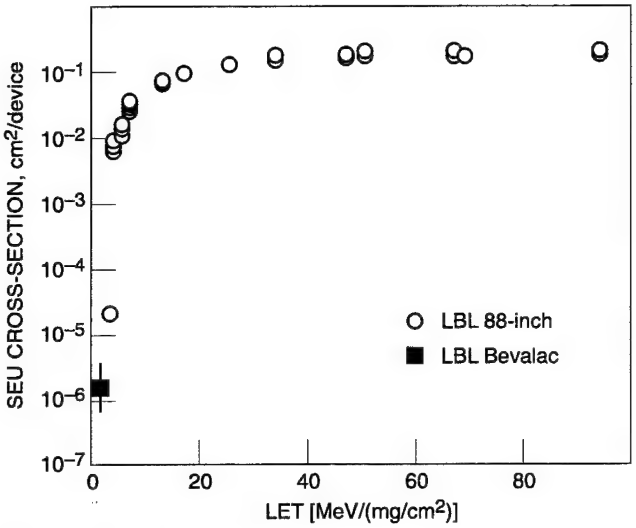

Figure 1. SEU test results for 32k×8 SRAM. The result obtained at the LBL Bevalac facility is superimposed on those measured at the LBL 88-inch facility.

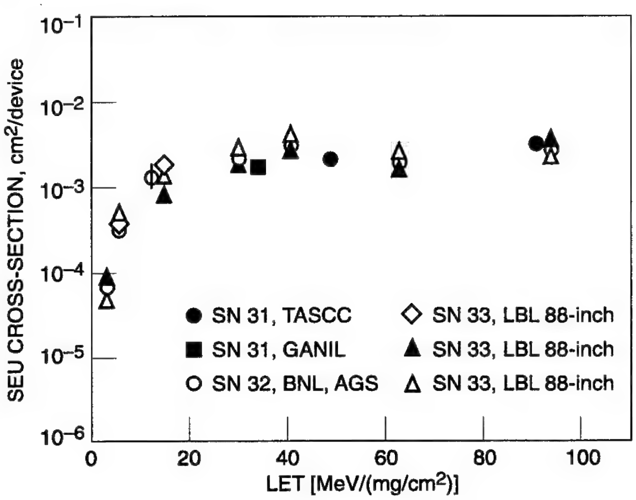

Figure 2. SEU test results for 128k×8 SRAM with ions of varying energies. Data at LET = 12.5, 34, 49, and 91 MeV/[mg/cm²)] were taken with AGS 11.4 GeV/n Au, *GANIL 4 GeV* Xe, *TASCC 1.6 GeV* I, *and TASCC 1.7 GeV* Au *ions, respectively.*

the same LET lead to higher charge collection at sensitive nodes [1,2]. The present study seems to indicate that no significant effects in SEU cross-section arise from using ions with a wide range in energy for the current test devices. The LET values of high energy ions in Figure 2 are located above the rising portion of the cross-section curve. The AGS test result at LET of 12.5 MeV/(mg/cm²) appears to lie close to those results obtained at LBL with Ar ions (LET = 15). One major difference between the previous study [1,6] and the current study is the complexity of test devices. Earlier works [1,6] deliberately incorporated simple semiconductor structures, while the current test devices are commercial circuits with multiple sensitive nodes. Therefore, it is possible that experiments carried out with a simple system such as an isolated PN junction may not be directly applicable to the current investigation in which the alteration of stored memory bits in complex circuits is considered.

There seems to be no systematic increase in SEU sensitivity due to ions of higher energies for the current test device types. Previous simulations and experimental studies [6,7] have revealed that charge collection processes in the epitaxial layer and multiple layer structures are very complex. Therefore, while the ion structure may be very important [1,2], a relatively complex geometry of sensitive regions in present microcircuits may make the direct association of track structure with the SEU sensitivity very difficult [6,7]. In some instances, the effect due to track structure may be masked by other factors. At even higher energies, we must consider the ion track structure of the primary, as well as those of the secondaries [3]. Therefore, the macroscopic observation manifested by the upset cross-sections of the present SRAMs may not have revealed the nature of the individual ion interaction.

The current study of SEU sensitivity of selected microcircuits has shown that LET appears to be a useful parameter even when a very high energy ion beam is utilized. SEU sensitivity may be expressed with the use of the existing plotting scheme, incorporating LET along the x-axis and the SEU cross-section as the y-axis. The concern that LET may not be an independent parameter (since ions of the same LET value with different energies promote preferred charge collection in some samples [1] and since a very high energy ion may leave widespread secondaries too scattered to be characterized by an LET value [3]) may not be applicable for the present test samples. At the region where the SEU cross-section begins to rise, observations of SEU sensitivity differences for ions of varying energies (with the same LET value) have been reported [4,5,15,16]. For the present test devices, the effect of ion structure seems not to influence the SEU cross-section in any noticeable way. However, the effects of track structure and issues associated with multi-layer structures need further investigation in order to determine their influence on SEU cross-sections of other and possibly more complex microcircuits. The LBL SEU test facility will continue to be an excellent place to carry out such a study.

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Electronic Device Technology

Short Pulse X-Ray Generation for Single Event Effect Testing of Electronics

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This report describes progress made during the first year of the Short Pulse X-ray Generation IR&D project, whose goal is to develop a facility for single-event effect (SEE) testing of electronic devices using short x-ray pulses. Microelectronic devices used in the space environment are susceptible to SEE due to passage of high energy particles [1]. SEE phenomena are traditionally studied at high energy particle accelerator facilities. Recently, ultrafast laser techniques have been developed for generating SEE in microelectronic devices [2,3] and have been shown to be reliable for hardness assurance [4]. Laser probing of device susceptibility has several advantages over particle beam techniques, in that (1) laser beams can be focused to small spots allowing location of sensitive nodes in complex integrated circuits (ICs) with submicron precision; (2) repeated laser excitation does not damage the material, whereas particle-beam excitation produces lattice defects; and (3) lasers are less expensive and more convenient to operate than particle-beam facilities.

The principal disadvantage of laser-based techniques for simulating SEE is that laser light cannot penetrate metalization [3]. Thus, a sensitive node completely covered with metalization cannot be interrogated using laser-based techniques. Because modern high-performance ICs have smaller devices, higher levels of integration, and multilevel metalization architectures, many complex ICs are covered with metalization and thus impenetrable to laser light. The ultimate goal of this project is to develop a facility using x-ray radiation able to penetrate layers of metalization to probe device susceptibility to SEE.

The objectives of this project are to investigate the feasibility of short pulsed x-ray generation for SEE testing, develop a laboratory facility, and establish the validity of short pulse x-ray SEE testing for hardness assurance. During the first year, our efforts have focused on determining the feasibility of and the most viable experimental approach for developing such a system. To be useful for hardness assurance testing, the system requires specific characteristics determined on the basis of this year's investigation.

Simulation of SEE requires not only that x-ray penetration depths in the material be appropriate, but also that sufficient quanta penetrate the metalization (e. g., *Al*, polycrystalline-*Si*, *Cu*) and oxide layers to produce SEE by charge generation within the active region. In order to simulate particle-induced SEE effects, the penetration depth in *Si* should range from a few to a few tens of microns. X-ray quanta between 0.8 to 5 keV produce such penetration depths in *Si*. Furthermore, our calculations indicate that quanta within the entire 0.8 to 5 keV range are adequately transmitted through simple oxides and one to two layers of metalization [5]. However, only quanta in the 3 to 5 keV range may be adequate for testing of devices with thicker oxides and/or higher levels of metalization or for devices containing *Cu* metalization. Thus, our investigations this year indicate that generation of x-ray pulses in the 0.8 to 5 keV energy range is required.

Typically, charged particles pass through semiconductor devices in 0.1 to 20 psec. Therefore, in order to accurately simulate charge generation effects of an energetic particle during SEE, the duration of the x-ray pulse must be ultrashort. Recently, ultrashort x-ray pulses have been produced using ultrashort laser pulses via: (1) high harmonic generation, (2) generation of ultrashort electron bunches that produce x-rays when launched into metal surfaces, and (3) laser ablation-induced generation of dense plasmas that emit x-ray pulses. Of these techniques, our investigations this year have indicated that the latter is the most feasible for producing pulses in the desired energy range and for focusability of the pulses. In this method, ultrashort bursts of x-rays are generated through the ablation of metal targets illuminated with intense fsec laser pulses [6]. The dense plasma produced by ablation generates mJ x-ray pulses with ultrashort pulse durations. Experimentation with structured metals revealed that x-ray generation efficiency is enhanced if targets such as gratings and porous substrates are used. The x-ray emission spectra depend upon the target metal chosen, but show efficient generation in the appropriate spectral range for *Al* and *Au* targets. Thus, we conclude that generation of intense ultrafast x-ray pulses in the desired energy range is experimentally feasible.

We have investigated methods of focusing these pulses to usable spot sizes. Recently, tapered monocapillary optics (MCOs) have been used to focus x-rays onto a sample [7], as shown in Figure 1. MCOs are

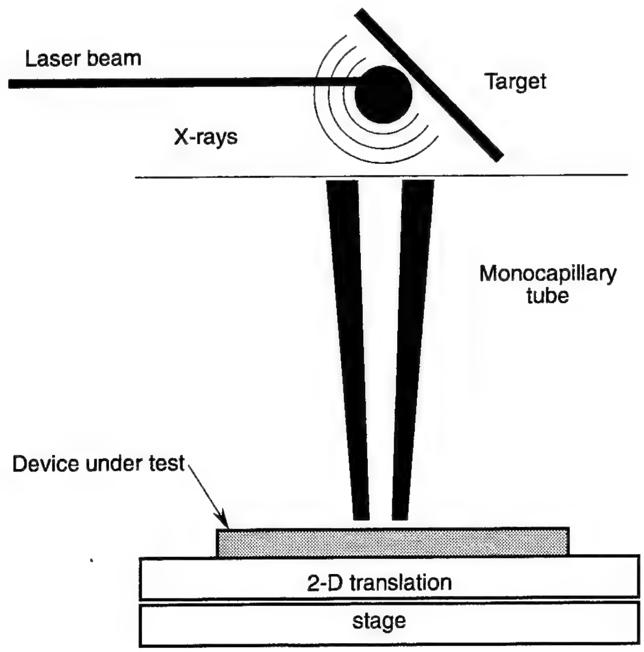
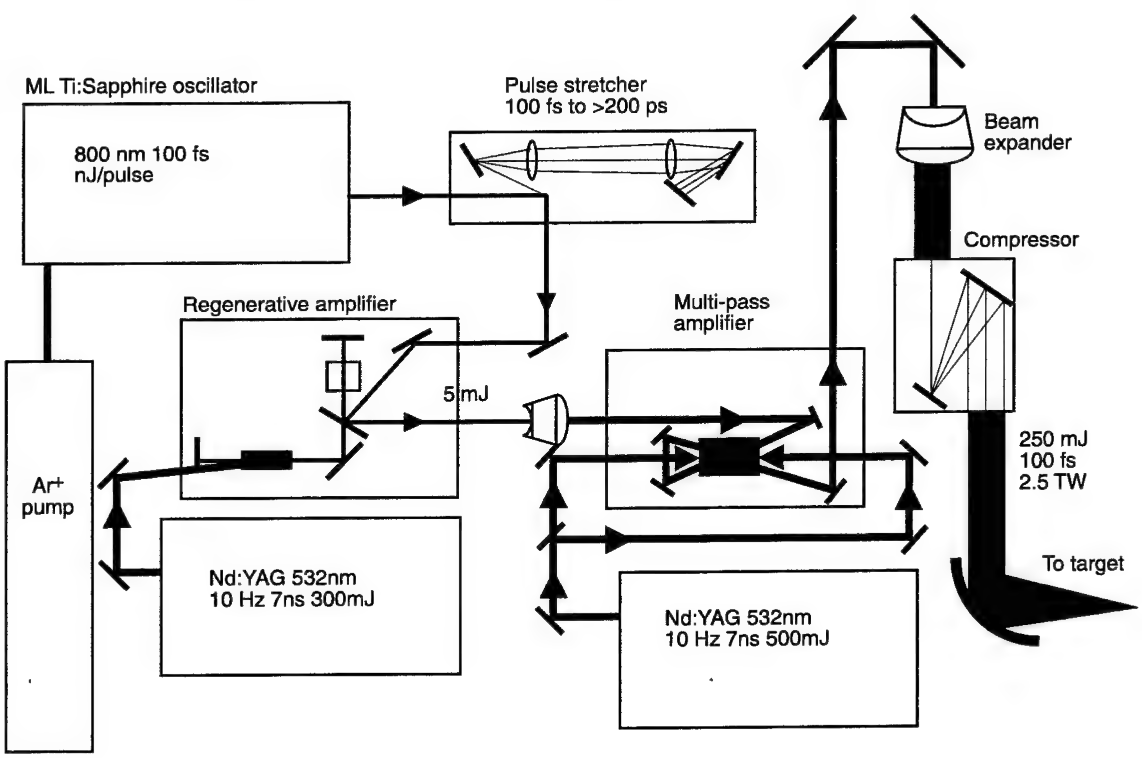


Figure 1. Collecting and focusing X-rays using a monocapillary tube.

hollow glass tubes that work as waveguides for x-rays via total external reflection. Efficient waveguiding of 1–10 keV x-rays occurs for input angles <0.2 degrees. MCOs with input end openings of 25 μm have been used to focus x-rays to diameters as small as 3.5 μm although nothing, in principle, precludes production of MCO tubes with exit openings of 50 nm or less [7]. This year we have performed parametric analyses of x-ray generation and collection by an MCO. Additionally, we have performed calculations comparing x-ray induced charge generation in semiconductor devices with charge generation by energetic particles. These calculations indicate that ultrafast x-ray pulse excitation of SEE will be possible even on devices with multiple layers of metalization and oxides.

Based on our investigation of the literature and the feasibility calculations we have performed this year, we conclude that it is feasible to develop such a system for SEE testing and have formulated an experimental design. The short-pulse x-ray apparatus we are developing is based on the laser ablation technique and is shown schematically in Figure 2. To generate a sufficient amount of x-ray energy from the plasma, extremely intense ultrafast laser pulses are needed. We have designed a laser amplifier system to generate these pulses based on a modelocked *Ti*:sapphire laser that produces 100 fsec pulses with a tunable wavelength ranging from 700–900 nm. The laser output is 1 watt at a repetition rate of 76 MHz. This is amplified in two stages. A regenerative amplifier increases the oscillator pulse energy from nJ to the mJ level. A second stage multipass amplifier boosts the pulse energy to 200 mJ. Prior to the first amplifier, the 100 fsec pulses from the oscillator are stretched to more than 200 psec in order to avoid laser-induced damage through the amplification process. Each amplifier is pumped by the frequency-doubled output of a Q-switched *Nd*:YAG laser. The output of the multipass amplifier is spatially expanded, recompressed to 100 fsec, and focused onto the target. The focusing optics and the target are enclosed in a vacuum chamber to prevent damage to the focusing optics, ionization of the air, and absorption

Figure 2. Schematic layout of the ultrafast laser apparatus for short-pulse x-ray generation.



of the x-rays by air. A portion of the x-rays generated is collected and focused, in a vacuum, onto the test device.

During the first year of this project we prepared a laboratory facility with a Class 1000 cleanroom unit enclosing a 4 × 18' floating optical table and the utilities required for laser operation. The *Ti*:Sapphire oscillator laser and the two *Nd*:YAG lasers for pumping the amplifiers are operational. The pulse stretcher, pulse compressor, and regenerative amplifier components have been ordered. During the next fiscal year, the first and second stages of laser amplification will become operational, and the laser will be focused onto metal targets to generate x-ray pulses. We will also develop methods for analyzing these x-ray pulses and focusing them onto small spots. In the third year of this project, these pulses will be used to simulate SEE in microelectronics and experiments will be conducted to validate the reliability of this technique for hardness assurance.

In summary, we are building an ultrafast x-ray source as a tool for excitation and location of SEE phenomena in future microelectronic devices. The quanta can penetrate multilayer metalization and still excite SEE. The system also has the potential to produce excitation in smaller regions than can currently be excited with laser spots. In the first year of this program, we have validated the feasibility of developing an x-ray facility and have begun the construction of the laser system necessary to generate the short x-ray pulses.

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Photonics for Space Systems

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The goal of this program is to investigate photonic components and concepts important to space-based optical communication systems. Our efforts during this first year focused mainly on radiation effects in *Er*-doped fiber amplifiers (EDFAs), which are key elements in high power transmitters and low noise receiver amplifiers for optical communications at 1550 nm. Previous studies have indicated that the sensitivity of EDFAs to radiation could preclude their use in the space environment. However, these conclusions were based on gamma irradiation tests, which are not fully representative of the space environment. For this reason, we initiated experiments involving protons, which are the most significant radiation threat to space-based hardware.

Since the radiation sensitivity of *Er*-doped fibers is strongly affected by the concentration of the *Er* as well as other essential ions, such as *Al* and *Ge*, we selected an initial representative set of fibers (detailed in Table 1) from a single vendor, Lucent Technologies, who offers a wide variety of these components. In our tests, we compared the transmission spectra of the fibers before, during and after gamma and proton radiation exposure. The amount of darkening, or color center formation, indicates the amount of damage induced by radiation exposure. It is the formation of these color centers that causes optical transmission loss, and hence, performance degradation of the fibers. For each fiber type, we cut several 3-meter samples to which we spliced standard single mode fiber at both ends. During the tests, one end of the standard fiber was connected to a white light source, and the other to an optical spectrum analyzer (OSA), as illustrated in Figure 1. The spliced EDFA fiber sections were then exposed to either proton or gamma radiation. Gamma irradiation was achieved using an in-house ^{60}Co source. Total doses up

Table 1. Erbium-doped Fiber Specifications (Lucent Technologies)

Model	Pump Level	Intended Uses/ Applications	Er Conc/m^{-3}	Co-dopants
HE980	15mW-70 mW pump	repeaters, first stage in multi-stage	4.25E^{+24}	*Ge/Al* (12M% *Al*)
LP980	2 mW-15 mW	battery-powered EDFA, first stage	7.80E^{+24}	*Ge/Al* (6M% *Al*)
MP980	70mW-150 mW pump	WDM, CATV, later stages in multi-stage	8.00E^{+24}	*Ge/Al* (12M% *Al*)
HP980	>120 mW	WDM, CATV, later stages in multi-stage	6.50E^{+24}	*Ge/Al* (6M% *Al*)
HG980		ASE source, radiation intensive	1.55E^{+25}	*Ge/Al*
R37003	25 mW-150 mW	WDM, CATV; booster, in-line, pre-amps	1.20E^{+25}	*La/Al*

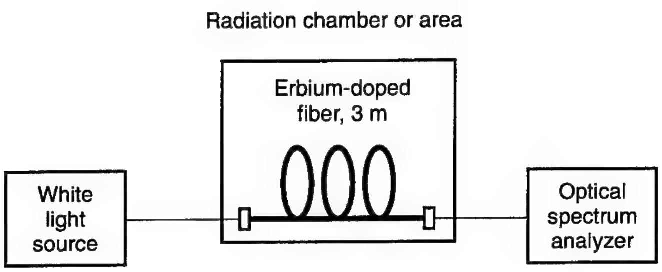

Figure 1. Experimental setup for radiation testing.

to 50 krads were obtained within a 10-hour time period; i.e., at a rate of ~1.4 rad/sec. Protons with an incident energy of 8 MeV were obtained at the Aerospace facility at the Lawrence Berkeley Laboratory 88-inch cyclotron. Exposure rates were significantly higher than for the gamma experiments, ~15 rad/sec, due to practical limitations of the experiment. For both irradiation experiments, transmission spectra across a range of 800–1700 nm were recorded at ~10-krad intervals. Using this broad spectral range, we could observe changes in transmission about the pump and the operational wavelengths of 980 and 1550 nm, respectively. Although damage is more easily observed at even shorter wavelengths, incident light below 700 nm was filtered out to prevent optical annealing, which is believed to occur from visible and near UV light. Figure 2 shows the change in transmission vs. proton and gamma dosage for all fibers in the region of 1550 nm. The results show that for each fiber, the damage caused by protons is significantly (2–3 times) less than that caused by gammas. At present, the discrepancy between proton and gamma damage is not well understood and is being further investigated. If this result is real, the survivability of these components in the space environment could be much higher than previously believed, thus making them more suitable for long-term missions in space.

In addition to radiation testing, we also began efforts to develop fiberoptic Bragg gratings (FBGs), which have numerous applications in signal processing, distribution, and timing. While standard FBGs are commercially available, non-standard structures for improved filtering and signal modulation require custom design. The development of in-house fabrication capabilities will enable us to generate narrow and steeply-sloped transmission devices that can enhance dense multiple wavelength systems' performance by reducing interchannel crosstalk. Additionally, this technology will allow us to shape the response of modulators implementing a FBG architecture, thus providing the means to improve efficiency and linearity. Our first Bragg gratings were written in commercially-available photosensitive fiber using a grating mask and UV light from an intracavity-doubled *Ar*-ion laser. A broadband light emitting diode (LED) at 1300 nm and an OSA were used to measure the grating in reflection and transmission mode (see Figure 3a). So far we have achieved 10 percent reflectivity with a 2 Å FWHM bandwidth, as shown in Figure 3b. While this reflectivity is more than adequate for fiberoptic sensing applications, near 100 percent reflectivity is required for efficient optical signal processing. We will continue to optimize our setup for improved performance.

In summary, in FY98 we examined radiation effects in EDFAs induced by both gamma rays and protons.

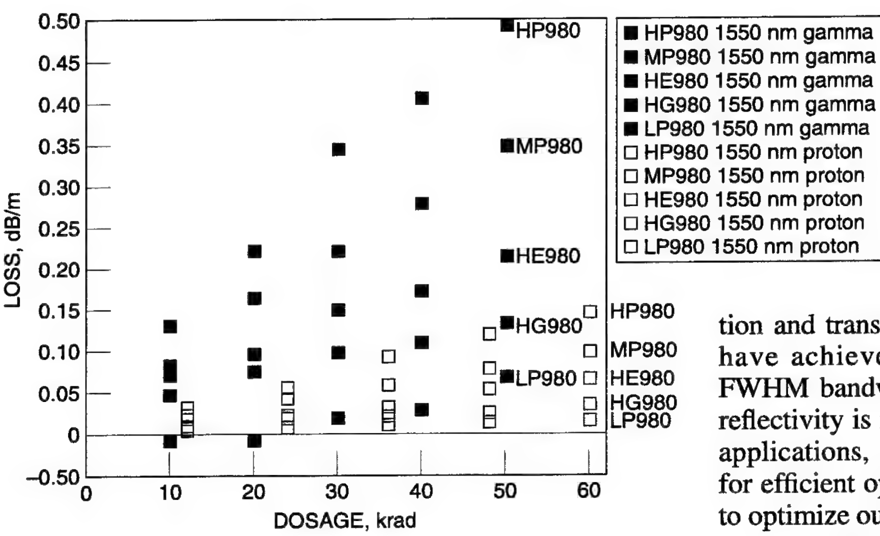

Figure 2. Transmission loss of all fibers at 1550 nm after gamma and proton irradiation.

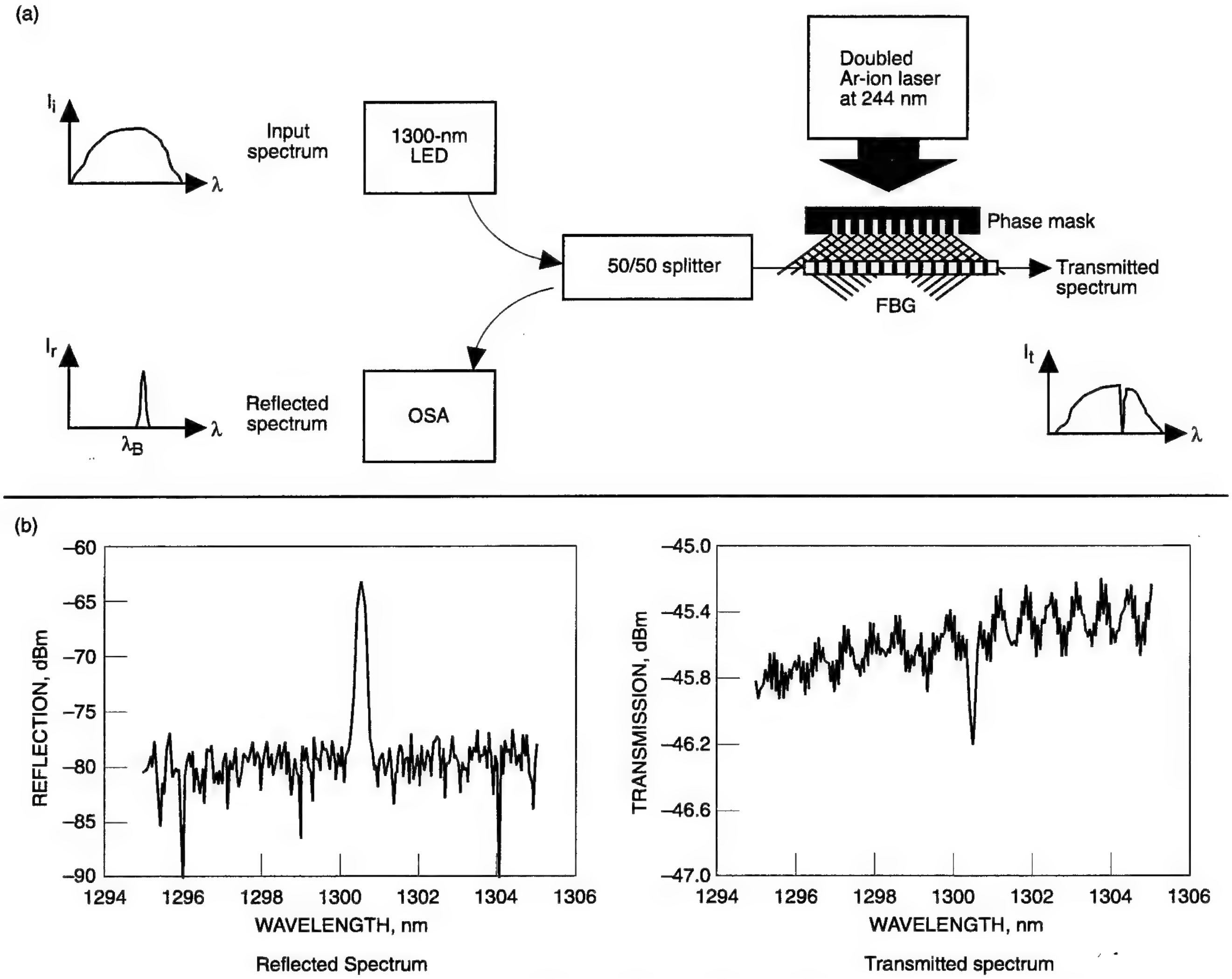

Figure 3. (a) Experimental setup for generating fiberoptic Bragg gratings and measuring performance. (b) Reflection transmission and spectra.

The large discrepancy between the amount of damage caused by equivalent doses for the two types of radiation is still being investigated. Our efforts in this area have gained the attention of various national defense space programs and Lucent Technologies, with whom we now collaborate. In addition, we have just begun fabricating FBGs, which have numerous applications in optical communications and signal processing. We will continue our efforts in this area to develop novel structures with unique filtering and modulation characteristics.

Multiplexed Fiberoptic Sensor Systems

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This report covers progress made during the last year of a program whose objective was to demonstrate multiplexed fiberoptic sensor systems for monitoring vibration, temperature, and strain for spacecraft applications. Much of the work described herein was conducted in collaboration with personnel from the Mechanics and Materials Technology Center (MMTC).

Fiberoptic sensors present numerous advantages for spacecraft systems, including low weight, EMI (electromagnetic interference) immunity, high environmental robustness, capability for providing the high density sensor multiplexing required for the development of smart structures and materials, ability to function in both embedded and surface mounted modes, and

utilization of serial deployment topologies that permit considerable simplification of the sensor interface buses. In this IR&D program we have investigated potential uses of Fiber Optic Bragg Grating (FOBG) sensors in space systems. Multiplexed networks of FOBGs are ideal for applications that require smaller, lighter, and ultimately, cheaper means for performing high-density distributed strain, temperature, and vibration sensing. An FOBG is a permanent, periodic spatial modulation of refractive index imprinted in the core of a photosensitive fiber optic by exposing it to an ultraviolet laser interference pattern. The grating reflects a narrow bandwidth of light with a peak wavelength determined by the grating spacing. Changes in temperature or strain alter the period of the grating, producing a shift in its peak wavelength that is proportional to that strain or temperature change [1, 2]. The shift can be directly measured using either a tunable Fabry-Perot filter or a monochromator, or it can be converted to an intensity change by passing the reflected light through a fixed frequency narrow band edge filter. Static and dynamic strain and temperature can be extracted from the measured wavelength or intensity changes of either serial or parallel arrays of FOBGs. The utilization of multiplexed FOBG networks in spacecraft and launch support systems will improve the performance of these systems and encourage the development of smart structures and materials for spacecraft applications.

During the first 2 years of the program we demonstrated vibration monitoring with an FOBG strain sensor mounted on the surface of a cantilever beam and showed that it reproduced the spectrum obtained with a conventional strain gage. Furthermore, the spectrum measured by the FOBG sensor was completely free of line voltage contamination (unlike the resistive strain gage), demonstrating the EMI immunity that makes fiberoptic sensors attractive. We designed a demultiplexing scheme capable of measuring vibration at up to ten locations with a 10 kHz bandwidth. We also developed [3] a conceptual scheme for ensuring the health and integrity of Composite Overwrap Pressure Vessels (COPVs), used in many spacecraft applications. Our approach employed surface-mounted FOBGs and an onboard, micro-electronic de-multiplexing module that continuously monitored adverse environmental stresses, such as mechanical impacts, pressure, and temperature. Additionally, we investigated the uses of embedded FOBGs in composite laminates to show that embedded sensors could be used to provide feedback to an intelligent manufacturing system (monitoring internal temperatures, degree of resin cure, resin shrinkage, etc.), as well as to detect the occurrence of environmental stresses that might compromise the strength and integrity of the composite part after fabrication. We embedded two sensors in a uni-dimensional four-ply laminated composite coupon and used them to monitor the level of internal strain and resin shrinkage during its cure cycle. In addition to resin shrinkage, we observed signals that we believe are the signature of delamination during cool-down of the composite.

During FY98 we investigated the application of fiber optic sensing to diagnosing the status of a spinning rotor bearing. We bonded a fiberoptic strain sensor to the fixed race of a spin bearing similar to those used in spacecraft reaction wheels, and installed it in a long-term bearing test station for the purpose of monitoring temperature and vibration levels during bearing operation. We showed that we could easily measure dynamic strain and its associated vibrational spectrum during normal operation. A typical spectrum, observed with a properly lubricated new bearing, is shown in Figure 1. The shaft rotation frequency was 34 Hz and the ball-pass frequency (i.e., the frequency at which balls pass a fixed point in the race) at this shaft rotation rate was 200 Hz. The strong signals observed at the shaft frequency and its overtones indicate slight rotor eccentricity and/or vibration. There is also a slight radial deformation of the outer race in the vicinity of each ball each time it passes a specific point on the race, resulting in a signal at the ball-pass frequency. A system of this type could be used to identify changes in the spectral signature that would denote bearing degradation. Such findings could enable the development of a "smart bearing" that would indicate the need for additional lubrication or provide a warning of imminent failure.

Solid Rocket Motors (SRMs) used in space launch vehicles are occasionally subject to impact damage. In fact, a recent Delta II launch failure was attributed to undetected damage in an SRM. Responding to Air Force concerns about this problem, we explored the feasibility of detecting potentially damaging mechanical impacts on SRM composite casings with fiber optic strain sensors. We instrumented an inert Delta II SRM at the Cape Canaveral launch facility and showed that the arrival time and magnitude of the transient strain signal produced by a low level impact depend upon the physical separation between the impact location and the sensor. A typical strain transient response obtained with an impact energy of $\approx$ 0.5 ft-lb (an order of magnitude smaller than the damage threshold) is shown in Figure 2. The upper trace was obtained with a conventional foil resistive strain gage, and the lower trace with a surface-mounted FOBG. The two types of strain sensors give very similar responses (although the FOBG signal-to-noise ratio is better), but the FOBGs are less obtrusive and easier to multiplex. In Figure 3 we have plotted the delay in arrival time of this transient from several impact locations. Impacts as distant as 15 feet could be easily detected with the FOBG sensor. Furthermore, the peak strain response was found to be dependent upon the intensity of the impact. These results strongly suggested that an array of FOBGs could

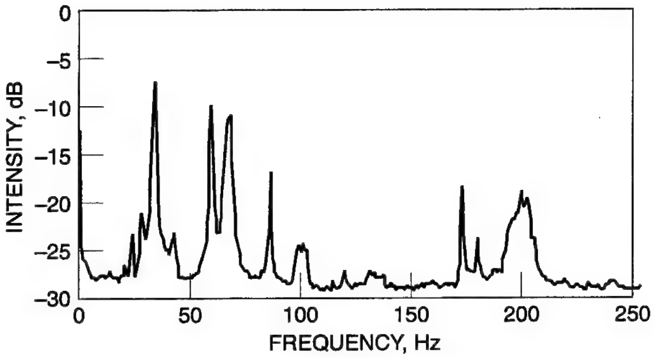

Figure 1. The vibrational spectrum of a spinning rotor bearing, measured by a fiberoptic Bragg grating sensor. The shaft rotation frequency of 34.2 Hz and its overtones, as well as the ball pass frequency of 200 Hz, can be easily seen.

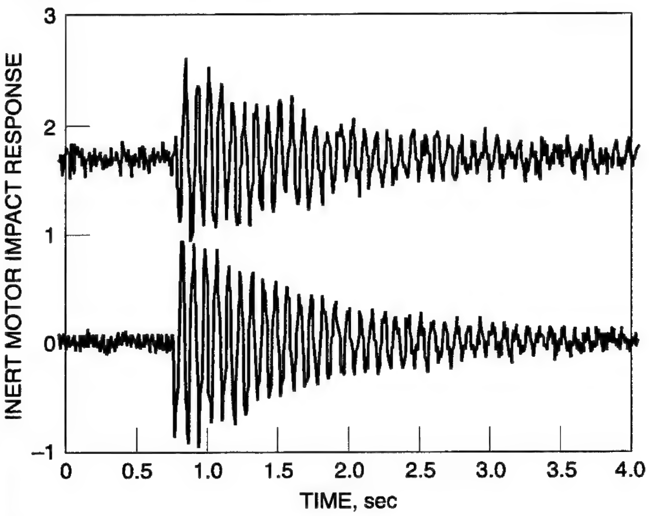

Figure 2. Impact transients observed with a conventional foil resistive strain gage (upper trace) and a fiberoptic Bragg grating sensor (lower trace) that were cemented to the surface of an inert full-scale DELTA II SRM located at Cape Canaveral.

be used in a fiberoptic monitoring system that would locate and assess the magnitude of impacts to graphite-epoxy composite SRMs. We then assembled an impact-sensing laboratory demonstration using a rectangular section (3 × 1 ft) of an SRM composite casing and four FOBG sensors. After developing appropriate signal-processing techniques, we showed that even low

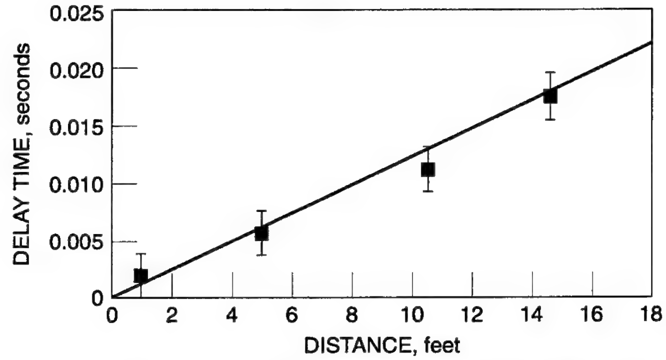

Figure 3. The dependence of the arrival time of the transient strain signal resulting from an impact to the inert DELTA II SRM on the distance between the sensor and the impact point.

intensity impacts (well below damage threshold) could be located with a positional uncertainty of + 2 cm. The success of our demonstrations on the inert SRM and the laboratory test article has resulted in the continuation of this work under Air Force funding. As we conclude our IR&D program on multiplexed fiberoptic sensor systems, we anticipate receiving continued Air Force funding in FY99 for the development of a full-scale, field-deployable prototype system for monitoring impacts on graphite-epoxy SRMs.

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Infrared Optical Parametric Oscillators

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This report summarizes the activities of the third and final year of this project, which focused on the development of infrared optical parametric oscillators (OPOs). These devices use a nonlinear optical material to convert the input (pump) beam into two beams of longer wavelengths, usually referred to as the signal

(shorter wavelength) and the idler (longer wavelength). By energy conservation, the sum of the signal and idler frequencies equals the pump frequency. An OPO provides a broader range of laser wavelengths than more conventional, fixed-frequency laser sources, making them attractive for many applications. The specific objectives of this project were to develop compact, highly reliable, continuous-wave (cw) tunable infrared sources for the calibration of satellite sensors operating at wavelengths near 3 µm and 4–5 µm, and pulsed sources for atmospheric phenomenology studies at eye-safe wavelengths longer than 1.5 µm.

In previous years, we successfully generated up to 450 mW of cw, tunable single-frequency OPO output near 3 µm, using the newly developed nonlinear optical material material known as "periodically poled lithium niobate" (PPLN). The technology was scaled up to a 5 W tunable OPO device near 3 mm, which was used to calibrate IR sensors on board spacecraft. This OPO system is better suited for remote deployment and more benign for the environment than the hydrogen fluoride (HF) chemical lasers used so far in most calibration operations. In the area of pulsed OPO development work, we demonstrated operation at the 1.57 µm eye-safe wavelength using potassium titanyl phosphate (KTP) as the non-linear optical material, delivering 7 W average output power at a 100 Hz pulse repetition rate without damage to the optical coatings. This performance level allows use of this device for cloud phenomenology studies, although higher output powers would be desirable.

This year we focused our efforts on developing a cw infrared laser working in the 4–5 µm wavelength range. Such a device is needed to calibrate second-color sensors on board satellites; there are no available laser sources for this particular application. The *HBr* (hydrogen bromide) chemical laser had been considered for this application, but none of its laser lines match the atmospheric transmission windows in this wavelength region. After our successful demonstration of the 2.9 µm PPLN OPO pumped by a *Nd*:YAG 1.06 µm laser, we proposed a similar OPO approach to develop a 4.5 µm source by using a newly-designed PPLN crystal with a modified grating period. In this configuration, 1.06 µm pump photons are converted into 4.5 µm (idler) and 1.4 µm (signal) photons. Since lithium niobate has a significantly higher absorption coefficient in the 4–5 µm range than in the 3 µm region (as shown in Figure 1), the OPO threshold to generate 4–5 µm output will be much higher than for 3 µm generation. Our initial plan to overcome this difficulty was to develop a 10 W single-frequency *Nd*:YAG pump source by scaling up the 5 W single-frequency *Nd*:YAG ring laser [1] developed earlier, and to use our pump-resonant OPO

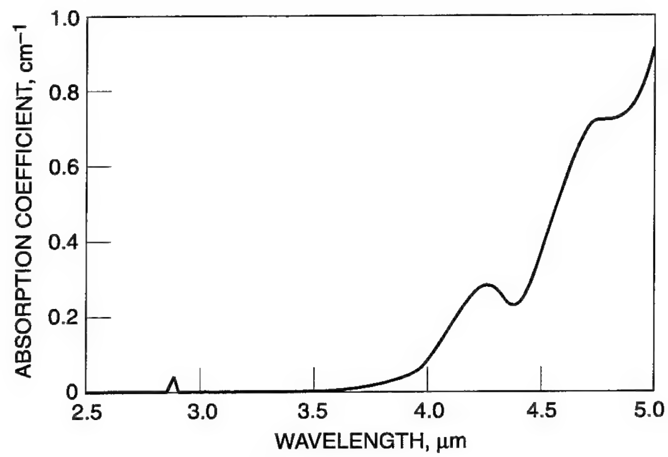

Figure 1. Absorption coefficient of lithium niobate material.

technique [2]. However, component problems prevented us from achieving sufficient output power to bring this new OPO up to the operating threshold.

We developed a novel approach, utilizing two steps of nonlinear conversion, to overcome the high threshold for one-step direct OPO generation at 4.5 µm. We proposed to generate from the 1.06 µm *Nd*:YAG pump a signal at 1.72 µm and an idler at 2.78 µm, exploiting the low OPO threshold at these wavelengths, and then use the 1.72 µm and 2.78 µm photons to generate 4.5 µm by a difference-frequency generation (DFG) process. A 55 mm dual-grating PPLN crystal was designed and fabricated; the first 50 mm performed the OPO generation, and the remaining 5 mm, with a slightly different grating spacing, performed the DFG process. Both processes were predicted to be phase-matched simultaneously at a 170°C PPLN operating temperature. The PPLN crystal was antireflection-coated for all the relevant wavelengths (pump, signal, idler and 4.5 µm). The advantage of this approach is that the DFG process used to produce the 4.5 µm output does not have a threshold. The threshold for the two-step conversion process is the same as for the first step, the OPO process.

This novel dual-grating PPLN device can be pumped by a cw multi-mode *Nd*:YAG laser. The experimental arrangement is shown schematically in Figure 2. With a 12 W pump input to the OPO/DFG cavity, we obtained 40 mW output power at a 170°C PPLN temperature. This is the first demonstration of an all-solid-state cw laser in the 4–5 µm region. The IR output was measured though a 4 µm long-pass filter. The output wavelength generated from DFG was 4.3 µm, somewhat shorter than our original predicted wavelength (4.5 µm). We attribute this discrepancy to uncertainties in the available values of the lithium niobate coefficients used for calculating the index of refraction in the 4–5 µm range. Correcting for the IR filter and OPO output

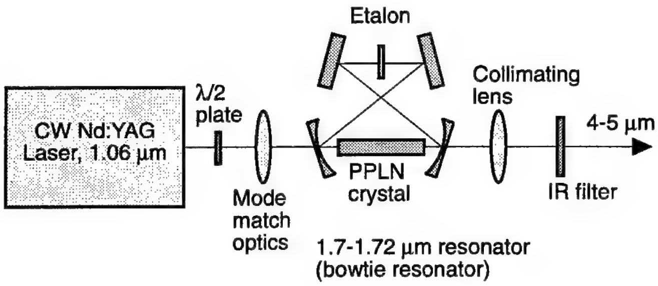

Figure 2. Optical parametric oscillator/difference frequency generation experimental schematic in the cw mode using a periodically poled lithium niobate crystal, providing a tunable output in the 4–5 mm wavelength range. The OPO/DFG is pumped by a Nd:YAG laser.

coupling losses at 4.3 µm, we estimate that the total cw power generated from the PPLN crystal is about 70 mW.

In summary, in the final year of this IR&D project, we have successfully demonstrated up to 70 mW of coherent 4.3 µm output using a novel OPO/DFG PPLN design. That output level would allow second-color calibrations, but with more accurate component specifications (e.g., PPLN grating periods, optical coatings, crystal temperature, etc.) the wavelength accuracy and output power of this 4–5 µm device could be substantially improved.

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Communications and Navigation Technology

Deterministic Noise Techniques for Secure Communications

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This summary report covers the activities and accomplishments for the sixth and final year of this continuing IR&D project initiated in FY93 (the project will be under alternative support starting next fiscal year). The project has focused on the development of a wideband, high-frequency communications system based on the recently discovered and potentially important capabilities of chaotic systems. The strategy adopted for this development entailed: (1) the design and implementation of a broadband, high-frequency chaotic oscillator; (2) investigation and demonstration of the chaotic synchronization between two such oscillators; and (3) the demonstration of chaotic modulation/demodulation with both analog and digital messages. Because of the novelty of this approach, the effort also includes the development of new engineering design methodologies; the assessment of the capability, merit, and feasibility of these new approaches in real-world communication scenarios; and the comparison of such approaches with classical techniques. The work this year involved the successful hardware validation of the breakthrough implementation approach discovered late last year, and ended with a start-up of the synchronization stage of the effort.

The relatively recent discovery of chaotic synchronization [1,2] has triggered a community-wide effort at harnessing the special properties of chaos for both baseband and RF communications. Such a chaos-based system would generalize current communications practices by replacing the traditional sinusoidal carrier with a chaotic one (either at baseband or centered around some RF frequency). The motivation for these efforts has centered around three basic aspects of the chaotic carrier, namely, its generation, synchronization, and modulation/demodulation with information. The basic characteristics of chaos, specifically its noise-like appearance generated from a well-defined and often simple underlying deterministic rule, makes it a natural candidate for hiding information with the dynamical rule as the key (implying low probability of intercept, privacy, and even encryption capabilities). Unlike a sinusoidal carrier, the chaotic carrier inherently provides some level of security without processing the information signal. The synchronization process itself—either based on unforced or forced chaotic systems—may prove superior to its classical counterpart with respect to speed, robustness, immunity to channel impairments and filtering, implementation complexity, and the like. Lastly, chaotic modulation may provide capabilities not even possible with traditional approaches, such as unique privacy and frequency reuse capabilities for wideband communications, tolerance to amplifier nonlinearities, and indirect schemes that have enhanced security and multiplexing characteristics. These and other applications of chaos to communications signal processing are outlined in reference [3].

Since its inception, this project has focused on the development of a wideband, high-frequency chaotic oscillator that would be a suitable basis for an operational communications system, handling either digital or analog information signals. This goal has been a significant challenge, beginning with a lengthy attempt at frequency up-scaling the well-known autonomous (unforced) generalized Chua's oscillator [4], which proved unsatisfactory, and ending with the turning-point discovery late last year of a new nonautonomous (forced) oscillator implementation approach, exhibiting superior preservation of baseband chaotic behavior. The basic lesson learned from this exercise was that the energy needed to sustain high-frequency chaotic oscillations is best delivered by an outside forcing source, and not from a negative resistance for which it is very difficult to maintain frequency independence over a wide operating range (because of unavoidable practical propagation delays and parasitics in the oscillator circuit). In addition, there are several advantages to a nonautonomous approach, the most important of which is that the chaotic synchronization process, at least from baseband observations, appears more robust against interference in the linking channel than its master-slave autonomous counterpart [2]. Our chaotic oscillator implementation heritage has been reported in [5].

The new oscillator implementation invented at the end of last year was based on the well-known forced Duffing equation derived from the modeling of mechanical spring systems [6]. This is a second-order, nonlinear differential equation in which a potential function manifests the required nonlinearity. A standard form of the system employs a third-degree polynomial potential function, which was replaced with a simple

piecewise-linear, three-segment continuous approximation. As a consequence, the phase space for the resulting system would consist of three regions, within which the system is essentially linear. This allows for a tenable qualitative analysis of the dynamics, and permits the emulation of the system by means of linear analog circuits whose parameters change as the dynamical orbit traverses from one region to another. Simulations demonstrated this system's remarkable tolerance to propagation delays in the associated amplifiers, permitting perturbations corresponding to as large as 90° rotation at the forcing frequency, yet still preserving the essential structure of the baseband chaotic dynamics. As expected, however, the propagation delay still limits the maximum frequency at which the system can be forced and remain chaotic.

This year's accomplishments have convincingly validated and significantly enhanced the aforementioned implementation methodology, resulting in unique Young-Silva Chaotic Oscillators (YSCOs), for which an Aerospace Invention Disclosure has been submitted for patent application approval, and highlight results have been published [7]. There are two versions of this design, a series- and a parallel-fed configuration, which are duals of one another. The series-fed circuit is ideal for use with operational amplifiers, as they have a low output impedance. The parallel version is well suited for use with collector- or source-loaded amplifier output stages (bi-polar and field-effect transistors, respectively) without feedback. The parallel version of the circuit is the most appropriate for use at microwave frequencies.

Chaotic oscillators built using this design contain the following elements: (1) a second-order passive subcircuit containing inductance, capacitance, and resistance (LRC subcircuit); (2) wideband differential amplifiers to provide each of two transmission paths; (3) a nonlinear element in one of the transmission paths to define the piece-wise-linear potential function (a diode limiter is one possibility); and (4) a source for a sinusoidal forcing signal. This is a relatively simple and direct method of producing broadband chaotic signals. An oscillator using this method typically exhibits a relatively flat power density spectrum that extends up to a corner frequency, at which point the spectrum rolls off gracefully. Also, the corner frequency can usually be placed well above the frequency of the forcing function, and the shape of the spectrum can be adjusted (another welcome feature of this approach). This oscillator is a natural candidate for indirect chaotic modulation, wherein the information signal is impressed upon the phase of the transmitter forcing function, while the frequency and phase of the receiver oscillator provides for synchronization (generalizing the action of a standard phase-locked loop) and demodulation.

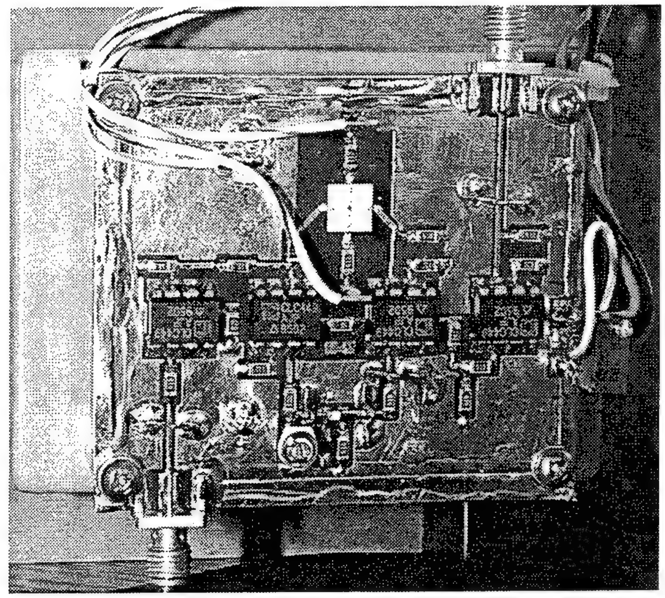

Figure 1. Digital photograph of an experimental YSCO implementation possessing a propagation delay of about 2 ns, resulting in an operational bandwidth of approximately 125 MHz. The necessary isolation buffers and input/output amplifiers are visible in the bottom part of the circuit board, while the diode limiter circuit that provides the breakpoints for the piecewise-linear nonlinearity can be seen in the top portion.

Several oscillators were built and demonstrated at increasing operational frequency ranges using the new design methodology. As reported last year, the first series-fed version operated at baseband (forced at ~10 kHz), and contained low-frequency operational amplifiers. These units were used to study the performance of the YSCO circuit design, and they will prove useful to the development of synchronization methods for application at high frequencies.

The first moderately high-frequency oscillator constructed used a two-stage, series-fed design containing current-mode, wideband operational amplifiers from Comlinear (CLC220). The circuit exhibited a propagation delay of less than 10 ns, and it preserved baseband behavior when forced at frequencies in excess of 25 MHz. The second oscillator was constructed in a similar configuration using Comlinear CLC449s, which are current-mode amplifiers with a 1 GHz gain bandwidth product (see Figure 1). The propagation delay here was less than 2 ns, comfortably allowing for a forcing frequency of ~100 MHz. The corner frequency could also be extended up to ~125 MHz by tuning the RLC subcircuit. Again, the baseband phase portrait was well preserved in qualitative structure, even though delays corresponding to rotation angles greater than 90° were approached at the forcing frequency. Experimental results from this YSCO are shown in Figure 2. This major achievement marked a convincing validation of our new oscillator design approach, and as far as we are aware, constituted the first demonstration of baseband-

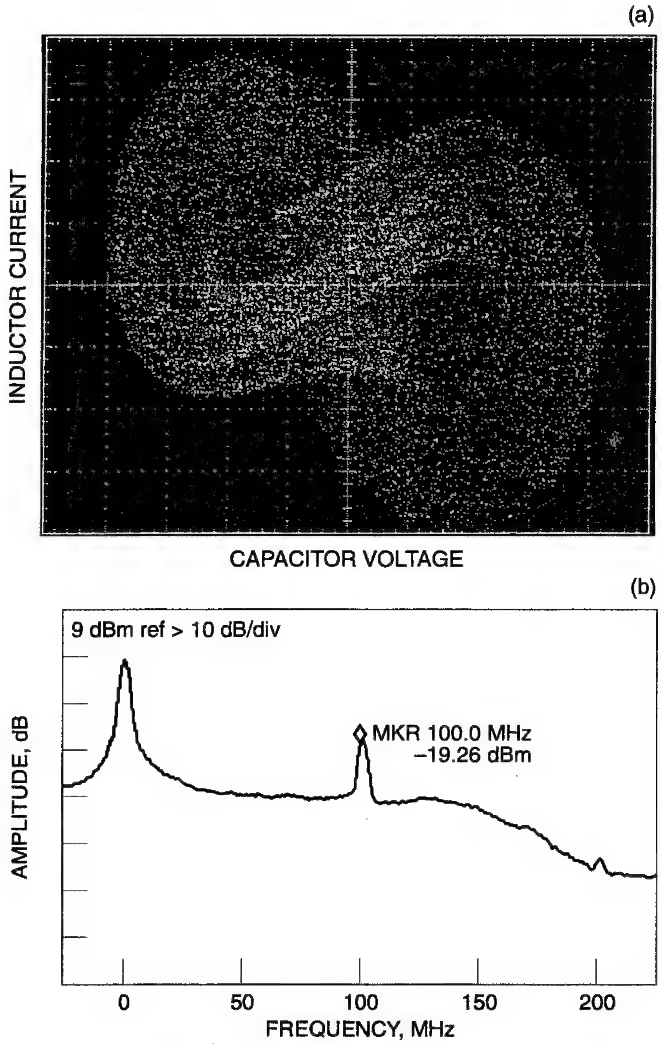

Figure 2. Experimental results from a YSCO driven at approximately 100 MHz. (a) Phase portrait that corresponds to the inductor current versus capacitor voltage. The majority of the qualitative features found at baseband are preserved in this high-frequency attractor, which was obtained using a digital sampling oscilloscope. (b) Typical capacitor voltage power spectrum, exhibiting a power peak at the forcing frequency and a corner point around 125 MHz. The spectrum shape is readily controlled by varying the amplitude and frequency of the forcing function, allowing, for example, the significant reduction of the source peak

preserving, wideband, high-frequency chaos from a nonautonomous oscillator.

A microwave version of the circuit was also designed, simulated, and laid out for fabrication. This is a parallel-fed design employing hybrid differential gain blocks that act as transconductance amplifiers; that is, their input voltage produces an output current. A gain block is used in each of two signal paths, where one path contains the required nonlinearity. A major advantage of this design is that the two signal paths can be combined by paralleling the outputs of the two gain blocks, resulting in an overall propagation delay that is only the delay produced by a single block. The expected delay here is on the order of 100 ps, which allows for a forcing frequency of ~2.5 GHz. In parallel with this final YSCO version, preliminary work was done on the synchronization of two of the previously constructed baseband YSCOs. Bi-directional coupling was used and synchronization was experimentally demonstrated.

In summary, the challenge of implementing wideband, high-frequency chaotic oscillators suitable for real-world communications has finally been overcome. The next steps for this continuing effort (which will be under other support starting next fiscal year) include: (1) construction, completion, and experimental demonstration of the microwave YSCO; (2) development and demonstration of the nonautonomous form of chaotic synchronization—beginning at baseband and moving up to microwave frequencies—including its characterization with respect to speed, lock-in range, and sensitivity to circuit and channel perturbations; and (3) development and demonstration of chaotic phase modulation using analog or digital baseband messages (speech to broadband data), and including standard performance evaluations such as probability of intercept, message privacy, interference/jamming resistance, and signal/noise ratio or bit error rate. Successful systems will be field tested in representative operational environments, evaluated with respect to their insertion viability/cost into current systems, and licensed for manufacture.

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QSSB/QVSB Digital Data Transmission

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The objective of this effort is to develop bandwidth-efficient digital data transmission schemes whose performance approaches the Shannon channel-capacity bound by employing quadrature single-sideband (QSSB) and quadrature vestigial-sideband (QVSB) techniques. These methods allow higher-rate data to be transmitted through a given allocated bandwidth—when compared to conventional methods—by maximizing the number of bits/s per Hertz. This report outlines the progress made over the second year of this effort.

With the advent of so many new wireless communications services, there is unprecedented contention for bandwidth resources. Recently, and for the first time in its history, the FCC actually auctioned off bandwidth for personal communications service providers. Cellular phone usage has increased to the extent that frequency re-use factors are routinely employed in comparing the capacities of the various competing systems. Higher and higher data throughput rates are needed as more digital services are being offered and integrated together, such as the Internet and ISDN (integrated services digital network). In addition, there is a demand to increase the quality and resolution of legacy services, such as CD-quality audio broadcasts and high-definition digital TV. Moreover, there continues to be an ever-increasing need to use available bandwidth more efficiently.

One of the main thrusts of this effort is to find signaling waveshapes of minimum bandwidth that exhibit relatively little crosstalk with quadrature carrier SSB/VSB transmission, thereby requiring only a modest increase in signal-to-noise ratio (SNR) over conventional double-sideband transmission. Additionally, modulator and demodulator/maximum-likelihood-sequence-estimator (MLSE) structures need to be developed. The MLSE developed during this effort should be able to unravel the desired signal from known or estimated crosstalk using the well-known dynamic programming optimization algorithm developed by Viterbi [1].

The initial task for FY98 was to evaluate the various options that were identified in FY97, namely: (1) time- and frequency-domain Nyquist filter descriptions; (2) partial-response (PR) signaling; (3) wavelets; (4) prolate-spheroidal waveforms; and (5) mutually orthogonal sequences, such as pseudo-noise, Gold, Kasami, Barker, Frank, multi-amplitude, and Huffman [2-8]. None of the orthogonal sequence families exhibited sufficiently small cross-correlation for practical sequence lengths. Our efforts during this year focused primarily on the first two signaling classes from which a group of candidate waveforms was screened using the crosstalk and inter-symbol interference (ISI) characteristics. The MLSE receiver has been developed to operate on crosstalk and ISI that exists over three data symbol periods. Simulated performance results for these signaling waveform candidates suggest that additional gains are possible using a more complex MLSE receiver that accommodates interference over a longer period of time. Development is currently underway to modify the MLSE accordingly.

To process the candidate waveshapes, QSSB and QVSB modulator/demodulator (modem) filtering structures were conceived, and coded in MATLAB® on a pulse-response basis. The modem filtering structure is not shown in this report because it may be patented. It differs from a conventional digital data demodulator in that each quadrature arm has two independent data channels that combine to yield a frequency-domain output that is on the order of half the normal bandwidth allocation. In the demodulator, these arms are appropriately filtered and combined to minimize crosstalk and maximize pre-detection SNR. To visualize more easily

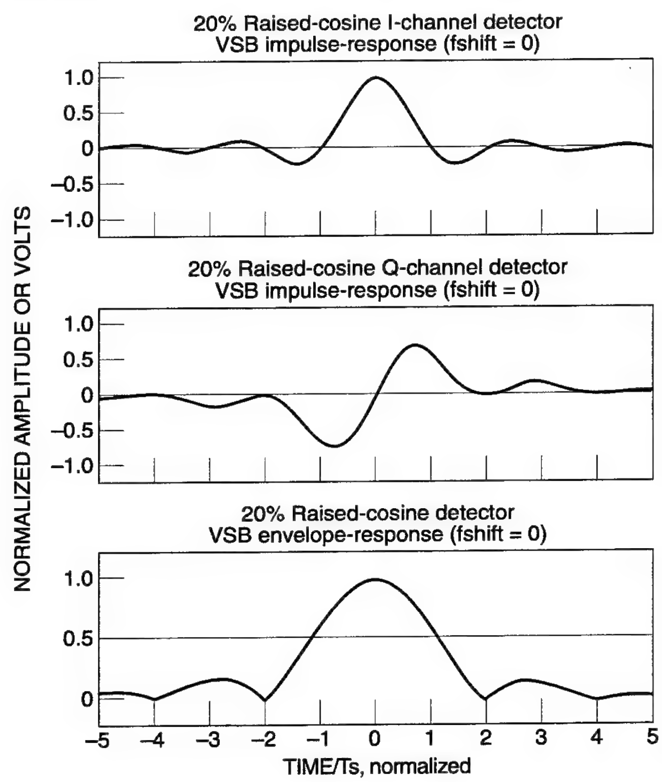

Figure 1. Recevier detector output, inphase, qudrature, and envelope impulse-responses, respectively, for VSB transmission with 20% raised cosine channel filtering

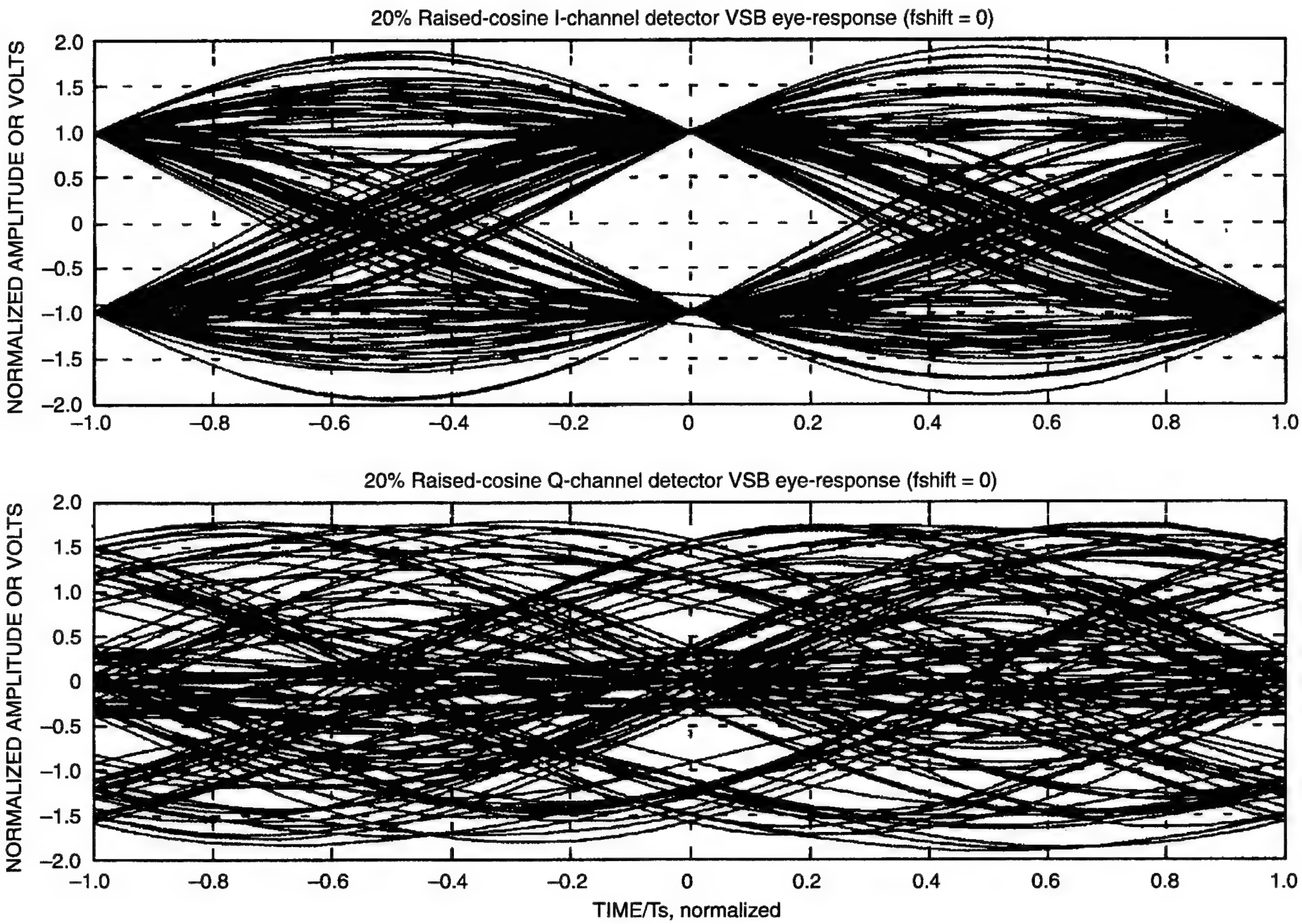

Figure 2. Receiver detector output, inphase and quadrature eye-diagrams, respectively, for VSB transmission with 20% raised cosine channel filtering

the effects of crosstalk, the inphase and quadrature (I&Q) responses of a single pulse for VSB transmission with 20 percent raised-cosine channel filtering are depicted in Figure 1. Since this is a Nyquist filter, the inphase response is a sin(x)/x-like function whose value will be zero at all integer data symbol times. One can imagine adjacent positive- and negative-going pulse responses (representing a data sequence transmission) superimposed on those shown in the figure. In the upper plot, these adjacent pulses will not interfere with one another at the detection sample points because of the equally spaced zeros. However, with QSSB or QVSB systems, independent data must be simultaneously transmitted through both I&Q channels, and interference will occur because the quadrature channel response only has zeros at even symbol time multiples. That is, with QSSB or QVSB, each channel will have complementary even and odd pulse responses that must be overlaid, resulting in ISI for both channels. The envelope-response for I&Q is given in the bottom plot within Figure 1.

To assess the effects of crosstalk more globally, the MATLAB® simulation was expanded to handle sequences of input data, rather than a single pulse-response. In this manner, eye-diagrams were obtained by overlapping all possible pulse-responses during a data symbol interval. The I&Q eye-patterns for VSB transmission with 20 percent raised-cosine channel filtering are depicted in Figure 2. In a conventional or SSB/VSB demodulator, the eye-diagram in the upper figure would be sampled in the center, at the maximum opening, and a 1/0 binary decision made depending whether the sample value was above or below zero. In this instance, the quadrature channel is given merely for illustration.

With QSSB/QVSB an independent quadrature data channel is added, and the I&Q demodulator outputs have no opening in the center, as shown in Figure 3. However, since the crosstalk that closes the eye is deterministically correlated to the data in the other channel (as shown in Figure 1), theoretically, the crosstalk can be removed with an MLSE.

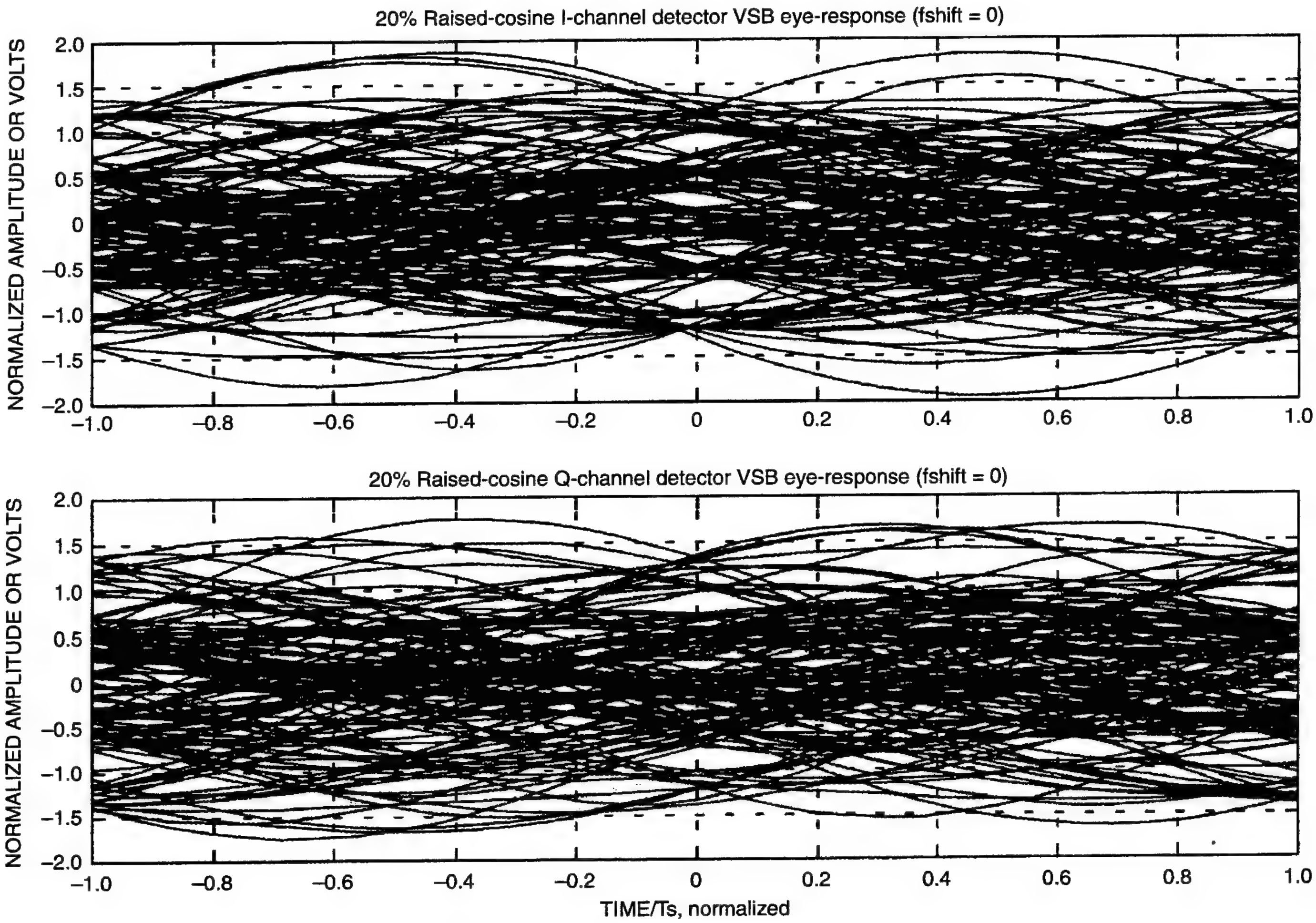

Figure 3. Receiver detector output, inphase and quadrature eye-diagrams, respectively, for QVSB transmission with 20% raised cosine channel filtering

It should be clear from this example that for each data symbol, ideally the MLSE needs to remove correlated crosstalk at all odd symbol time multiples: ±1, ±3, ±5,.... However, in practice, only the crosstalk at ±1 and ±3 is dominant. This greatly simplifies the complexity of the MLSE, which grows geometrically in complexity with the number of time samples in the aperture. To date, an MLSE that operates over ±1 has been coded up and debugged. Extending this MLSE to ±3 is under development.

The performance of the MLSE is critical in determining whether it will be worthwhile to continue down this path. Preliminary simulation results (performed using the three-symbol aperture MLSE) suggest that this approach provides an advantage over conventional techniques (in terms of bandwidth-efficient signaling with a minimal impact to required SNR). Thus, our efforts to date have yielded: (1) a viable set of candidate waveforms for use in a QVSB/QSSB communications system, (2) a filtering structure that would be used with these waveforms, (3) a specialized MLSE receiver algorithm to recover the transmitted symbols in the presence of severe crosstalk and ISI, and (4) a MATLAB® simulation for assessing the performance of the transmitter/receiver structure. The ongoing work involves an extension of the MLSE algorithm to accommodate more symbols in the receiver aperture. It is hoped that the modified MLSE receiver will be able to successfully unravel the correlated crosstalk with an even smaller impact on the SNR required. Subsequent QVSB/QSSB filter design work is also expected to be done where wavelets are applied to constant envelope modulation techniques [9] (earlier identified as a promising filtering approach). All results will be published following a comprehensive performance assessment of each transmit/receiver structure. A patent disclosure is also anticipated.

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Information Science

High Performance Computer Communication Networks

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Computer networks have become essential components in almost every aspect of space systems, and they are increasingly recognized as a very high-leverage factor for achieving information superiority. The Internet, which is the interconnection of diverse networks, has grown exponentially over the last few years, and with the introduction of the World Wide Web, its applications have been expanded commensurately in both scope and variety. Furthermore, the Internet has become increasingly heterogeneous in terms of speed, delay, capabilities, and mobility. In the current networks, links ranging from asymmetric high-speed satellite links to low-speed radio links for hand-held devices all need to operate seamlessly to efficiently support military applications. Consensus-based standards such as Transmission Control Protocol/Internet Protocol (TCP/IP) see increasing use by the military to support command and control activities both at headquarters and in the field. Computer networks is a rapidly-evolving field driven by the convergence of the telecommunications and computing marketplaces, where new applications are continually emerging. New technologies are being adopted and old ones are being superseded at a faster pace than in almost any other field.

The Air Force, NRO, and many other customers recognize that in order to maintain information superiority they must take advantage of this rapidly changing field or risk technological obsolescence. A vital component in winning a modern-day war is realtime access to and integration of multiple sources of reliable intelligence and reconnaissance information. Information gathering, collection, maintenance, and dissemination for defense purposes rely heavily on computers and networks. Many Air Force programs have begun to explore and exploit new network technologies, including Asynchronous Transfer Mode (ATM), satellite-based, and wireless networks for achieving information superiority. These newer technologies offer additional capabilities and services, such as the inherent broadcast nature of the Global Broadcast Service (GBS) and mobility support with wireless networks. More importantly, newer networks and protocols support the kinds of communication services that new information systems applications demand. Chief among these applications are distributed parallel computing (metacomputing) and multimedia computing, including Web-based technologies.

These advanced applications require new functionality from the underlying networks, such as assured transmission of very large and/or compressed imagery, handling data from video sources (e.g., Unmanned Aerial Vehicles (UAVs)) and audio sources, and critical messaging applications such as Air Tasking Orders. They also require more traditional applications, such as Web browsers and protocols such as Hyper Text Transfer Protocol (HTTP), as well as traditional file and stream data services. In addition they demand the ability to make reliable connections among a group of computers (e.g., multicasting), whereas today's networks typically support the establishment of only point-to-point connections. Problems of security and network fault tolerance—which are not addressed well by current networks—must also be solved. To plan for the transition of those programs to the next generation of network technologies, we have undertaken the evaluation, development, and deployment of selected high-speed networking technologies to problems of importance to Air Force and other national programs.

The long-term objectives of this project are to evaluate leading-edge high-speed network technologies, to develop and demonstrate communication protocols needed for high-speed, low-latency, reliable and secure data transfer, and to develop network management software to manage large, heterogeneous, high-speed networks. A dominant theme in our work is the greater use of commercial off-the-shelf (COTS) hardware, protocols, and software to meet unique program requirements via open standards.

Our progress in FY98 was built upon our efforts in FY97, when we expanded our laboratory facilities to include an ATM network, a satellite link emulator, a high-performance Myrinet, and a wireless network to test and evaluate emerging network technologies. The ATM network consists of 155-Mb/s (OC-3) optical fiber and wire links joining high-bandwidth packet switches and host interfaces. Experimental work on the Aerospace ATM network, which was connected to the ATM Research Consortium (ARC), was completed during FY97. During FY98, we purchased a newer

ATM network with wide area network (WAN) connections to UCLA and USC Information Sciences Institute for supporting network-based high-performance applications. Unlike older local area network (LAN) and WAN technologies that only provide best-effort delivery of data, ATM supports the integration of data, voice, and video traffic in a single network, thus paving the way for new network-based applications such as multimedia computing and desktop videoconferencing [1].

In FY98, we focused on four inter-related areas: (1) efficient Internet Protocol (IP) protocols and multicast in networks with asymmetric satellite links, (2) wireless networks research, (3) high-performance parallel computing, and (4) computer network/enterprise management. Below we briefly explain the progress made this year in each area.

In order to better support internet services in a GBS network, we explored several different approaches for efficiently supporting the TCP/IP protocols using asymmetric satellite links [2,3]. Over the course of the last year, we continued development on our two major software contributions—VIPRe and PitVIPRe—for use with the GBS satellite link. PitVIPRe protocol software provides a non-ATM solution to the asymmetric route problem, at the expense of platform dependency. Currently, PitVIPRe is implemented on Solaris, as a Solaris STREAMS module, together with a modified version of the standard Solaris network configuration utility program, which loads the new module into the network stack. The prototypes of the network tunneling software, VIPRe and PitVIPRe, were successfully tested over the actual GBS satellite link at the DARPA Advanced High-Performance Computing facility. The VIPRe technique was submitted as an Internet Draft Standard this year and is being discussed in the Internet Engineering Task Force.

Multicast capability is becoming an important requirement in the Internet as newer applications demand this service. In the military battlefield, multicast service is valuable to provide reliable information to a large number of personnel. The GBS network provides a natural means for dissemination of data. However, multicast services over such links is non-trivial. We successfully demonstrated multicasting in our testbed using the satellite link simulator and the VIPRe protocol. We are currently evaluating reservation based protocols (RSVP) in the heterogeneous networking environment.

In this project we have continued and expanded our research on achieving a wireless Internet capability using hand-held computers. This offers a low-cost approach for sending and receiving data to the "last mile" of satellite-based networks for the warfighter, such as GBS. In FY97, we successfully demonstrated such a wireless capability using an Apple Newton MessagePad 2000 as a portable platform. We are continuing our research in this area to experiment with smaller and more robust radio links, and provide a wider suite of supported Internet protocols, such as multicast. This would allow sound and video to be transferred wirelessly to a hand-held unit. The related Satellite Link Mobile Mesh Multicast (SLAMMM) IR&D project is demonstrating such technology.

An emerging network technology is multi-hop wireless networks, where there is no wired network infrastructure support. Networks where all hand-held computers cooperatively maintain network connectivity are called ad hoc wireless networks. Ad hoc networks are useful in any situation where temporary network connectivity is needed without a backbone wired infrastructure. For instance, consider the problem of establishing a temporary wireless network in a battlefield or in a region hit by some natural disaster. Assuming that one or more of the nodes of an ad hoc network in such an area were connected to the Internet, this network could enable medics in the field to retrieve patient history from hospital databases, provide a method for disseminating realtime targeting information to the battlefield, or allow for the collection of the location and status of troops. Building such ad hoc networks poses a significant technical challenge because of the many constraints imposed by the environment. The devices used in the field must be lightweight. Furthermore, since they are battery operated, they need to be energy-conserving so that battery life is maximized. Several technologies are being developed to achieve these goals by targeting specific components of the computer and optimizing their energy consumption. We have developed energy-conserving network protocols suitable for ad hoc wireless networks [4,5].

In the area of distributed parallel computing, we successfully implemented the Nexus runtime system, which was developed last year in cooperation with the Aerospace Parallel Computing project as well as with Caltech and Argonne National Labs. We implemented a remote data visualization capability with relevance to commercial and defense meteorological image processing applications, which allows an inexpensive workstation to be used as a display for a numerically intensive visualization computation running under VIS5D, a data visualization software package from the University of Wisconsin. These extensions were incorporated into the Nexus release maintained by Argonne National Labs, which is used to support supercomputing and data visualization over wide area networks.

In High Performance Computing (HPC) applications, including scientific computing, signal processing, and meteorological image processing, high throughput can be achieved using systems with large numbers of nodes. Examples of such machines include the IBM

SP2, Cray 3D, Intel paragon, etc. In these systems, the array data to be processed will be distributed among the memories of different nodes in the system. An application may consist of several stages of computation, and at each stage, optimal distribution of data to processor memories is critical to minimize performance penalty. Therefore, data redistribution operations, such as data cube rotation or corner turn, will be required to improve the efficiency of applications. Data redistribution operations require communication among the processor nodes in a system, and we have developed communication scheduling algorithms to perform such operations efficiently [6,7].

This IR&D project achieves synergy between our networking research and on-going enhancements to the computing infrastructure we use on a daily basis. In cooperation with the "CSD Automation Initiative" Engineering Methods project and the Corporate Information Resources Division (CIRD), we expanded the ATM-based local area network beyond the network laboratory workstations to many desktop machines using the newly-delivered local area network emulation (LANE) service. Currently, we have most of the laboratory workstations using ATM exclusively for their network connectivity, while most servers and some desktops are dual-homed on ATM and Ethernet.

As the leader of the ATM Research Consortium (ARC) project, Aerospace was responsible for the coordination of a wide area ATM network connecting some eleven premier institutions in Southern California. Now completed, ARC was the only California Research and Education Network (CalREN) project that Pacific Bell extended with full funding. This effort has allowed us to gain greater insight into the maturity of ATM technology and the relative merits of emerging commercial products. The various projects under ARC include performance measurements, evaluation and modeling, distributed processing, and others. In addition to Air Force programs, these same technologies offer great promise for a number of non-traditional applications, such as telemedicine, remote telescopy, architectural visualization, distance learning, video conferencing, data mining, teleradiology and others [8].

In the area of network management, we incorporated new technologies into our laboratory and evaluated them in cooperation with the UC Davis Computer Science Department. This included the InCharge system from System Management Arts, which uses powerful codebook-based algorithms to rapidly perform distributed event correlation. In the area of computer network security, we applied an early release of InCharge to the problem of information survivability with emphasis on network management and intrusion detection scenarios. High volume event correlation paradigms were studied in order to detect coordinated attacks for scaleable large heterogeneous networks. This collaboration with UC Davis formed the basis for the DARPA-funded GlobalGuard project. We are also collaborating with UCLA researchers in this area and developed a proposal for rapid and secure data dissemination in the Internet. Software tools to monitor and analyze network traffic to detect intrusions were developed at Aerospace in collaboration with the Harvey Mudd College Computer Science Department.

The High Performance Computer Communication Networks IR&D project continues to make rapid progress towards its primary goals of evaluating, demonstrating, and using leading-edge computer network technology, even as the network technology, the commercial marketplace, and the space business continue to evolve at an accelerating pace. This year we successfully demonstrated VIPRe and PitVIPRe protocol software and tested their performance with the GBS asymmetric satellite link at a DARPA facility. In cooperation with other DARPA-funded programs, we are developing the capabilities to perform multicasting over asymmetric links. Our research on power-aware protocols for ad hoc wireless networks contributes toward expanding the scope of the SLAMMM IR&D project. In cooperation with other activities in the Air Force-funded Parallel Computing project, as well as our DARPA-funded work, we have developed a collaborative visualization capability that can operate across heterogeneous networks. We have developed the necessary components to enable high-speed, secure communications among cooperating parallel processes, and have demonstrated these components by implementing a remote data visualization capability with relevance to commercial and defense meteorological image processing applications. We have developed and analyzed new protocols for multihop wireless networks that have relevance in defense battlefield networks.

The research results, protocols, software tools, and high performance computing application demonstrations hold promise for all national security programs, which are demanding the ability to share large amounts of data over great distances and to distribute functions throughout a theater of operations.

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Satellite Link and Mobile Mesh Multicast (SLAMMM)

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Military networks are increasingly heterogeneous, with satellite links and terrestrial networks having to interoperate seamlessly to disseminate data in the battlefield. Wireless mobile computing and communication environments are major components of military networks: they permit the rapid dissemination of tactical information to mobile units in the battlefield, and the real-time collection and integration of reconnaissance information from spaceborne, airborne, and terrestrial nodes. For example, a direct broadcast satellite link, such as the Global Broadcasting Service (GBS), can disseminate information to battlefield tactical units that are equipped with wireless portable computers. Wireless terrestrial networks can extend the reach of satellite-based networks to reach forward deployed units and lower echelons. The efficient and reliable operation of such a heterogeneous network is vital for achieving information superiority.

Computing and communication technologies in support of this environment are maturing rapidly, particularly in the areas of portable computing devices and wireless communications. However, although current internetworking technologies have been successful in linking large numbers of computers and users, they are oriented towards computer interconnections that operate in a stable environment composed of terrestrial wired nodes. One problem, for example, occurs when a unidirectional satellite broadcast system that has multiple downlink sites is combined with a terrestrial wireless network. Since nodes in the terrestrial network may not be in the footprint of the satellite, it is not clear how to determine which downlink site forwards the data to the remote nodes, what route(s) to use, or how to ensure that the data delivery is reliable and efficient. The infrastructure for an environment that combines satellite links and mobile mesh needs further development, especially in the area of reliable, efficient, multicast routing protocols.

Multicast protocols and multicast-based applications are increasingly important in the Internet. The types of services offered by these applications are of value in heterogeneous networks; however, the existing protocols are not well suited to mobile wireless networks. Multicast routing protocols support the transmission of a single message to multiple recipients. For example, instead of transmitting a situation awareness update to each recipient on a battlefield individually, a multicast protocol would first construct a multicast distribution tree that spans the networking infrastructure between sender(s) and receivers. It would then use this tree to minimize replication of the data being sent to the receivers, replicating the data only where the tree branched. Satellite links provide the ability to simultaneously transmit data to multiple receivers in the satellite's "footprint," and as such, provide a powerful communications resource in a battlefield environment. However, the incorporation of unidirectional satellite links violates the path-symmetry assumptions made by many of the multicast protocols used in the "wired" Internet. The increased probability of loss experienced in radio and satellite networks also negatively affects the ability to provide a reliable multicast service. Mobility and signal fading of the nodes in the mobile mesh introduce frequent topology changes and complicate path discovery algorithms.

The purpose of the Satellite Link and Mobile Mesh Multicast (SLAMMM) research effort is to examine the technologies that support multicasting in mobile mesh environments, and to determine whether those technologies are applicable to the type of heterogeneous environment that will be prevalent in the battelfield. The project will adopt, adapt, or develop technologies as necessary to provide effective multicast services in

an environment consisting of wired, mobile mesh, and satellite links. The research goals of this project are as follows:

- Investigate the efficient and reliable operation of multicast routing protocols in heterogeneous network environments
- Analyze and simulate these protocols
- Demonstrate their use with Internet-based applications in an experimental testbed environment that includes satellite links and mobile nodes

This is a collaborative research project between The Aerospace Corporation and The MITRE Corporation that started in March 1998. The research is organized into three teams, each staffed by members of both corporations. The first team is conducting protocol analysis and design, and is jointly led. The second team is developing the demonstration and experimentation environment, and is led by the Aerospace Corporation. The third team is developing a discrete event simulation environment and relevant simulation models, and is led by the MITRE Corporation.

This year, we pursued four major activities on the SLAMMM project, namely: (1) agreeing on a set of research issues; (2) developing an understanding of relevant system architectures (including equipment type, placement, and traffic); (3) developing a demonstration plan; and (4) developing a simulation plan.

The first activity, establishing a set of research issues, is largely complete. The set of research issues identified includes evaluation of existing multicast protocols and potential extension of those or development of new multicasting protocols, analysis and development of channel access mechanisms suited for multicast transmission in mobile mesh environments. We then proceeded to investigate the research issues listed above, and obtained partial results for each of them.

Multicasting Protocols: Multicasting in an ad hoc network requires (possibly partial) topology discovery, path building, and data transfer to destinations. To the extent that topological information is available from unicast routing tables, it can be used to reduce control traffic in the multicast protocol. To perform efficient multicasting there may be considerable control overhead in finding near-optimal paths to the destination nodes. We started our evaluation of multicast protocols by defining a set of performance criteria along with accompanying ideal bounding metrics, namely:

- Delay—basis of comparison: shortest path tree
- Bits transmitted—basis of comparison: Steiner tree (possibly dynamic ST)
- Robustness (probability of receipt)—basis of comparison: flooding
- Traffic concentration—basis of comparison: link-disjoint shortest-path source trees

We surveyed the literature and identified three different approaches to ad-hoc multicast routing that are currently proposed as Internet drafts [1, 2, 3], and started analyzing them. We hope to complete our survey of ad hoc multicast protocols and publish our results early next year.

Channel Access Protocols: In wireless networks, when a node transmits, the radio signal will be received by other radios within a certain distance called its range. The range distance depends on the power of transmission, the noise and other channel characteristics. Since each radio transmission will be heard by all the neighboring nodes, if one or more nodes within range transmit simultaneously then they will collide and the transmission will not be successful. To ensure proper communication, there cannot be interference during a transmission. For this purpose, we need a channel access protocol that determines which node can transmit at a given time. There are several schemes, such as TDMA (Time Division Multiple Access), MACA (Multiple Access with Collision Avoidance), MACAW (Multiple Access with Collision Avoidance for Wireless LANs), FAMA (Floor Acquisition Multiple Access), etc., that have been proposed in the literature for channel access in the context of unicast routing. The problem is made more complex when one must arbitrate the use of the channel among multiple receivers, some of which may be busy. A trade-off exists between link utilization and delay in this situation. Another important consideration is the effect of overhead computations on the power consumed by the wireless radios.

We began to analyze the existing channel access protocols for use in the SLAMMM architecture. We developed an approach for measuring the efficiency of different channel access schemes and their ability to reduce the control overhead needed to support multicast traffic. We documented our initial findings in [4, 5, 6].

The second project activity was to develop a SLAMMM architecture. Our baseline communications architecture is focused on transporting multi-destination traffic. As such, the architecture was developed to utilize a mix of communications media that can provide unicast, multicast, and/or broadcast transmission capabilities. The communications media include GBS, fixed high capacity radio links, mobile lower capacity ad hoc radio nets, and Unmanned Aerial Vehicles (UAVs).

We developed a three-tiered architecture that uses the First Digitized Division Tactical Internet (FDD TI) for the terrestrial component and includes GBS links from a Theater Injection Point (TIP) to multiple GBS receivers that are interconnected via fixed high-capacity, full-duplex, point-to-point terrestrial links. A subset of the GBS receivers is, in turn, connected to mobile users via lower capacity, half-duplex, shared radio

networks. In addition, we include the availability of a UAV for moderate capacity, full-duplex broadcast support of a subset of fixed and mobile users.

We envision a set of approximately 10 Tier 2 elements and 25–100 Tier 3 elements, depending on how many of the lower echelon units are included. The number of Tier 2 elements is approximately half that planned for the TI but is adequate to capture network characteristics. The number of Tier 3 elements is chosen to reflect roaming brigade elements and company commanders who require/desire communication. The exact number and placement of Tier 2 and 3 elements is the subject of continuing discussion and research, as are the details of the radio characteristics and laydown/mobility/terrain scenarios. The SLAMMM architecture and the service characteristics defined so far are described in more detail in [7] and are illustrated in Figure 1.

The third project activity was the development of a demonstration plan for multicasting in an ad hoc network. Our demonstration plan is centered on developing a person-wearable system that combines computing, input/output, and communication resources. These resources are being integrated into a vest, and being combined with advanced antenna and battery technologies. Each vest will represent a wireless node in the SLAMMM testbed. The testbed will also include a satellite link, which will be simulated using the Aerospace satellite link emulator in the initial stages of the project, and a wired network.

We investigated wireless radios for use in our testbed and selected the Spirit radios by Rooftop Corporation because they are the only multi-hop tranceivers currently available commercially. We defined a three-stage schedule for our experimental demonstrations, to be conducted in October 1998, March 1999 and August 1999, respectively.

The main purpose of the Stage 1 demo will be to validate the mobile node component of our SLAMMM testbed by demonstrating a simple Web application in a wireless environment based on the Rooftop Spirit radios. For the Stage 2 demos, we plan to demonstrate the transmission of still digital photos from mobile users to a simulated command structure and unidirectional multicast transmission from the command structure to multiple mobile users. The multicast data will involve voice (background situation reports, local weather forecasts), pager services (broadcast commands, weather reports), and slow frame videos (forward reconnaissance, big picture battlefield). We plan to add the satellite component of the architecture by using a GBS feed if one can be made available;

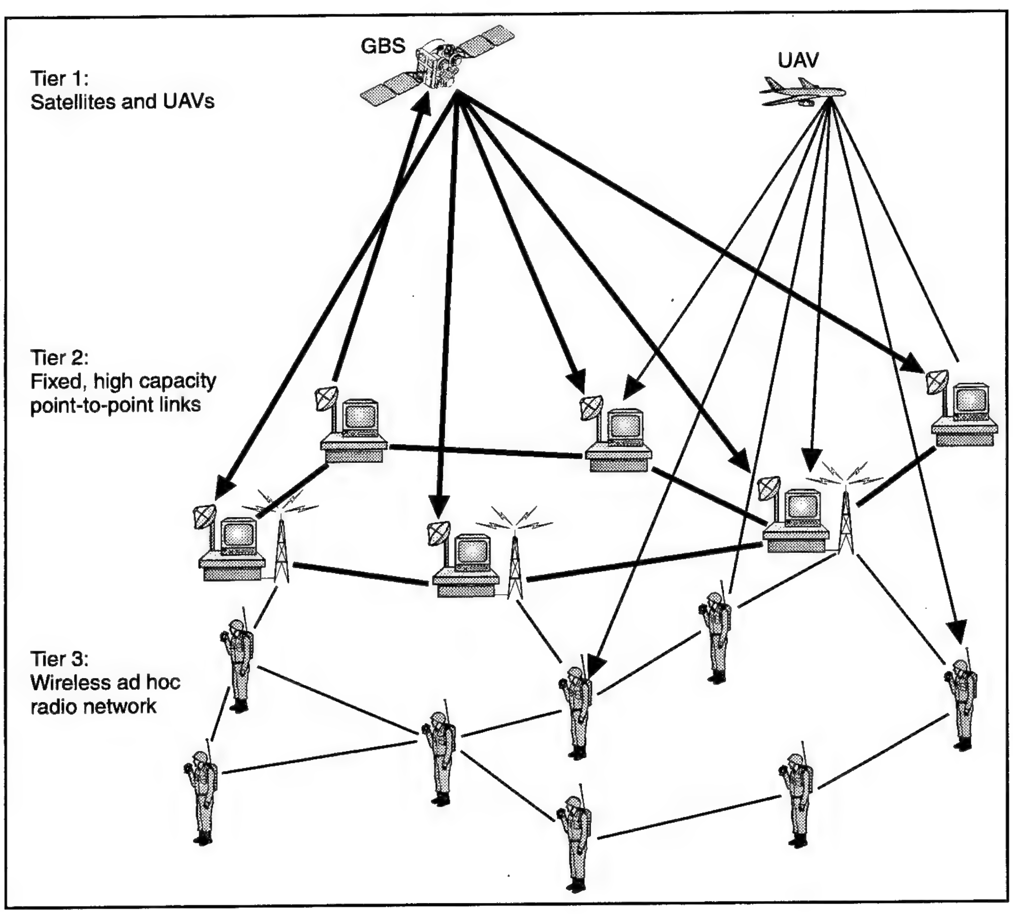

Figure 1. Three-Tiered Communication Architecture Envisioned for SLAMMM Research

otherwise we will use an Aerospace-developed satellite emulator. We will also develop the security mechanisms necessary for protecting the information transmitted over the mobile wireless networks used in the demonstration. Stage 3 demos will include multiple bidirectional multicast voice and video transmissions between the command structure and mobile users and among mobile users, as well as receiving information from forward-deployed remote sensing devices such as video cameras, vibration sensors, chemical sniffers, etc.

The last of the four project activities involved developing a simulation plan for the project. The environments in which these protocols will be deployed are not easily demonstrated on a large scale, and simulation is a tool that will enable examination of protocol performance with less cost and time than fielding full-scale demonstrations. We are currently defining and performing a simulation trade study to select a simulation package for use on the project. This selection is affected by a number of factors, and revolves around two simulation packages: PARSEC, a parallel processor simulation developed at UCLA that can handle thousands of nodes, and OPNET, a well-known commercial simulation package that has an established DOD use base. To determine which simulator will be used, a common representative module, Distance Vector Multicast Routing Protocol (DVMRP), available in both OPNET and PARSEC, was chosen and will be tested under both packages. This will allow a direct comparison of the two in terms of accuracy of protocol modeling, occurrence of coding/logic errors, ease of use, run-time speed, and memory requirements. We expect the selection of a simulation package to be competed by the beginning of FY99.

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Information System Technologies

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Information is now viewed as the key to the continued dominance of our military forces. The emerging model for future information systems, both military and commercial, is a push-pull information architecture based on the Internet, incorporating groupware and collaboration tools to support interaction between users. In this architecture, users are provided easy, on-demand access to distributed information repositories while autonomous programs, called agents, proactively search and disseminate important information to users. Groupware and collaboration tools allow distributed teams to interact in realtime and to share information easily. The objective of this project is to explore and develop innovative technologies and products for building future information systems.

During FY98, this project investigated a number of technologies important to future military information systems, including intelligent agents, groupware, realtime collaboration, extensible markup language (XML), and Java. As these technologies are making their way into commercial products, it is becoming increasingly important to evaluate commercial off-the-shelf (COTS) software. This year, we installed and tested a number of innovative commercial packages including Netscape Suitespot, Microsoft NetMeeting, ICQ (a collaborative internet locator), Netscape Conference, the DataBeam

Learning Server, and IBM ViaVoice. The evaluation of these commercial products is proving that some technologies, such as realtime collaboration, are ready to be used in current information systems, while other products, such as inexpensive commercial voice recognition, are not as robust as hoped. Still, the promise of all these technologies is clearly evident.

With the growth in the popularity of the Internet, numerous companies have developed Web or HTTP (hypertext transfer protocol) servers for serving documents over the Internet. However, future information systems will require additional features including messaging, collaboration, calendar and scheduling, directory information, and security. These features are starting to appear in commercial products. For example, Netscape's Suitespot, a highly-rated collection of servers, implements these features and also provides centralized administration and real-time media streaming. Suitespot's servers are all based on existing or upcoming open standards and easily integrate with other standards-based products. In order to evaluate this standards-based approach to providing these capabilities, quite a bit of time was spent installing and testing the 10 servers that make up Suitespot. During this evaluation, we found that intelligent integration of these servers, as provided by Suitespot, provides more capabilities than the sum of the individual servers. The servers work together to provide a more powerful and easier to administer combination. For example, the Directory Server contains information about users and groups; once specified, this information can be used across multiple servers. The Certificate Server provides security that is used to restrict access, authenticate users, and encrypt data for the remaining servers. The Certificate Server also takes advantage of the Directory Server in order to store user certificates. In this manner, each of the servers can take advantage of the features provided by the other servers.

Seven of the 10 servers—the Enterprise Server, Directory Server, Certificate Server, Collabra Server, Calendar Server, Catalog Server, and Admin Server—were installed and tested. The remaining three servers, the Messaging Server, Proxy Server, and Media Server, were of less interest but still covered in the evaluation by reading their documentation and reviews. At the end of the evaluation, our results were summarized in a briefing that is available on the Aerospace Intranet. Although we found Netscape's product a little difficult to administer, we found the standards-based approach to building an information architecture very promising and recommend it over proprietary solutions.

As the Web browser is becoming the universal front end for information systems, Web-based application development is becoming increasingly important. Netscape's interest in this area was clearly evident in Suitespot. Suitespot supports Corba IIOP, provides application interfaces in C, C++, and Java, and supports relational database access. Using Suitespot, a prototype team application was developed providing a discussion group, shared document repository, shared calendar, an HTML (hypertext markup language) help interface, and security restricting access to members of the team. Currently, the main limitation of Web-based application development is on the client side, where the interface is usually restricted to either unstructured HTML or a Java applet, which is still not well supported by Web browsers. As Web-based client interfaces become more dynamic and Web-based development environments improve, this may become the preferred environment for the development of future ground systems.

Intelligent agents are autonomous programs performing tasks on behalf of a user. For example, an agent could monitor a telemetry stream for anomalies. When an anomaly of interest to the user occurs, the agent could check the user's calendar to locate him and inform him of the anomaly. In prior years of this project, a framework called the Web Agent Framework (WAF) was developed for creating intelligent agents on the Web and used to build a number of agents. During FY98, this framework was enhanced with a new server providing persistent storage. This server was developed using new features in Java 1.1. Java's Remote Method Invocation (RMI) allows the server to be easily accessed across the network and Java Serialization allows any Java object to be stored on the server simply by implementing the Serializable interface. The server also provides password-based security on groups of related objects. Although developed for WAF, this server is general enough to provide remote persistent storage for almost any project.

Handling realtime data over the Web is a difficult task. Caltrans has developed a site displaying current traffic conditions on the Los Angeles freeways that is updated approximately once a minute. In order to test working with realtime data, a traffic-monitoring agent was developed. This agent allows a user to specify a route on the freeways (e.g., 405N between El Segundo and Santa Monica), a time period (e.g., between 3:30pm and 4:00pm), and a condition (e.g., traffic moving <25mph). The agent then monitors the Caltrans website and notifies the user via a Java applet, email, or a pager that the condition has changed. Although this type of agent can be very useful, it is also fragile due to the nature of the web and HTML. If Caltrans makes the slightest change in its HTML to change the appearance of its Web site, it could render this agent useless until the HTML parsing is updated. This is one of many reasons for studying a new standard for text markup languages, called XML.

In contrast to HTML, which is a fixed markup language designed to represent the appearance of a document, XML is not a single markup language, but rather a meta-language that lets users design their own markup language. XML is used to define customized markup languages, allowing structure and meaning to be contained in the document. For example, <state>Washington</state> shows that Washington is the state name instead of a person's name, but it does not specify how it should be displayed. Like HTML, XML is viewable and editable on any platform. Since XML is an open standard, it is vendor- and platform-neutral, and allows users to select any complying tools to generate, exchange, or process XML data.

XML is important to Aerospace and our customers for a number of reasons. First, XML is expected to become the standard language of the Web in the near future, with support for XML coming in Web browsers, including Netscape Navigator 5.0 and Microsoft Internet Explorer 5.0, databases, and office suites, such as Microsoft Office 2000. XML also enables a number of Web-based applications. XML may be used as a data exchange format to connect databases and software applications, and to integrate data from multiple sources. Since data is tagged with its meaning in XML, searches can be more accurate than the current keyword searches. Since XML is structured data, after being delivered to the client XML can still be parsed, edited, and manipulated, with computations performed by client applications. XML separates data from display by using style sheets to define the data's appearance. Data can be presented in different ways without changing the XML by providing a new style sheet. Thus, applications processing XML do not need to worry about changes in the data appearance modifying the data, as did our traffic-monitoring agent.

There is a rapidly-growing list of markup languages being developed for various purposes using XML. A few of the more relevant languages for Aerospace include: Resource Description Framework (RDF), Open Software Description Format (OSD), Web Interface Definition Language (WIDL), Mathematical Markup Language (MathML), and Astronomical Markup Language.

During FY98 we studied the whole family of XML technologies, including the XML 1.0 Specification, XML Linking Language (XLink), XML Pointer Language (XPointer), XML Style Language (XSL), and XML Namespaces. We wrote and published an introduction to XML on the Intranet and produced a tutorial for XML, XLink and XPointer. In addition, we studied several markup languages, including those mentioned above, for their potential applications. Next year, we plan to define an experimental telemetry markup language using XML and to develop a client to publish telemetry XML data from the Advanced Satellite Workstation (ASW).

Online collaboration between geographically separated teams is becoming an important feature of information systems. For example, online realtime collaboration would allow Aerospace, government, and commercial personnel to provide "virtual launch support" without requiring any travel. In addition to the development of the team application using Suitespot, we evaluated a number of commercial products used for realtime collaboration. Products offering realtime text chat and shared whiteboards have been around for some time. Current collaboration products offer new features that could greatly enhance the effectiveness of these teams. Products such as ICQ and Instant Messenger locate other team members when they are online regardless of their location. Products such as Netscape Conference, Cu-SeeMe, and NetMeeting provide audio and video conferencing over the Internet. NetMeeting also provides a feature called application sharing, allowing users on separate computers to view and interact with the same application, even if the application is only installed on one of the computers. Currently, NetMeeting only supports the PC platform, but products supporting standards-based cross-platform, application sharing are starting to appear.

Vendors are also developing products for online presentations and education. We installed and tested two such products, the Real Encoder/Player from Real Networks and the DataBeam Learning Server. The Real Encoder/Player is in wide use on the Internet and allows live presentations to be streamed across the Internet or Intranet and recorded for later viewing. It is relatively easy to set up, provides reasonable quality, and could be used to broadcast presentations or video of a launch over an Intranet. The DataBeam Learning Server is designed to conduct live training over the Internet or Intranet using a Java-enabled browser as the client. It allows administrators to prepare a course catalog, schedule courses, and register students. Teachers can use it to provide course materials to students and conduct real-time classroom operations, including text chat and application sharing. Students may browse the course catalog and class schedule, register themselves, download course materials, and attend classes. During our testing, we exercised all of these features. At this point, the lack of audio conferencing and poor performance of application sharing are its most critical weaknesses. If audio conferencing, and perhaps even video conferencing, can be incorporated in future releases, such products may be useful for training employees and military personnel.

In connection with the presentation software, we considered creating a searchable archive of audio

presentations. Inexpensive continuous speech recognition products are now available from a number of vendors and would provide the audio-to-text conversion necessary for performing keyword searches. During FY98, we installed and tested trial versions of IBM ViaVoice and Dragon Naturally Speaking. Both products are speaker-dependent, requiring users to go through a training period to be most accurate, limiting their usefulness in this type of application. Unfortunately, even after training, the products correctly recognized only approximately 80–90 percent of the words. Along with ViaVoice, IBM has available a programming interface adhering to the beta Java Speech Application Program Interface (API). The API provides for both speech synthesis and speech recognition. The API also allows developers to specify what phrases the product should expect to hear, such as options in a menu, in which case recognition was far better. Although the performance of both products left something to be desired, the promise of the technology was clearly evident.

Throughout the year, we tried to remain current with technologies surrounding the Java programming language and take advantage of new capabilities. During the past year, the performance of Java interpreters has been further improved and a new graphics library called Swing is being added to the core Java language. With these improvements, we feel Java is a reasonable alternative for large-scale application development and should be considered for future ground system development.

In FY98, we used Java to further enhance our agent framework, develop the traffic-monitoring agent, and test the Java Speech API, all mentioned above. In addition, we created a class library for distributing Java applications called the Distributed Class Loader (DCL). One of the main advantages of Java applets is software distribution. Java applets are downloaded over the Internet at runtime by the Web browser, providing automatic distribution and guaranteeing that the user has the most recent version of the software. DCL provides these same benefits to Java applications by replacing the default class loader to allow Java classes to be downloaded over the Internet. DCL is meant for use on secure networks, such as an Intranet, and does not have the security restrictions of applets. Also, unlike applets that run in a Web browser, a reasonably large application, the DCL client is less than 10K in size.

The Information System Technologies IR&D is investigating and developing innovative technologies for the development of future information systems. We believe push-pull information architectures, intelligent agents, XML, Java, and online collaboration will all be important parts of these systems. In the future this project will continue to explore new information technologies and develop prototypes demonstrating their use in future information systems.

Joint Technical Architecture (JTA) Evaluation and Experimentation

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The DOD has mandated that the Joint Technical Architecture (JTA) information system standards be used in all new and upgraded command, control, communications, computer and intelligence (C4I) systems and interfacing systems. The JTA mandates the use of the Defense Information Infrastructure Common Operating Environment (DII COE), a collection of information system products that include government- developed and commercial software, along with rules for putting them together. The Air Force Acquisition Executive has requested that all programs list their current standards, compare these standards with the JTA, and develop a migration plan to ensure JTA compliance. In responding to this request, a number of SMC and NRO program offices have asked Aerospace for technical advice and assistance in their consideration of migration paths to accomplish JTA compliance. The JTA and COE mandates can be viewed as two (recent) components of the more general drive to increase interoperability between military systems and promote software portability and reduce software cost, all in support of information superiority.

This report covers the first year of the JTA IR&D project. The purpose of the project is to broaden our technical understanding of the issues affecting portability and interoperability between information systems, to develop expertise in the use of JTA standards and COE products, and to influence their future direction. The project consists of the following four tasks: (1) analyze current JTA standards, and their relationship to technology trends and to our customers' needs; (2) survey emerging space-related information system standards; (3) experiment with COE products and architecture rules; and (4) influence the integration of selected new technologies into COE.

Our analysis of JTA standards started with a comparison between JTA and the Integrated Open Systems Standards Profile (IOSSP). The IOSSP is a reference

document for information system standards that was developed by Aerospace in parallel with the JTA [1]. The IOSSP describes standards activities in all areas of information systems. It gives an assessment of the different standards and protocols that are currently available as well as the ones that are under development, and provides guidance on whether or not to use each of these standards—and if so, when and how to use them. The IOSSP was put on contract by some of our customers before JTA became a requirement for them, so we undertook a task to analyze Aerospace's recommendations in the IOSSP and compare them with the corresponding requirements in the JTA. We found that the two documents are organized differently, and that unlike the JTA, the IOSSP contains no mandates regarding the use of any standards, but rather recommendations for the timeframe of their use. Additionally, IOSSP contains extensive explanations regarding each of the standards areas along with background information on the chronology of the different developments. No inconsistencies were found between the two documents. However, we found three areas that are included in the JTA but not in the IOSSP: oceanographic data interchange standards, atmospheric data interchange standards, and MILSATCOM standards. Nevertheless, because the IOSSP provides more details on the standards contained in both documents, we decided to turn the IOSSP into a reference document for JTA, and proceeded to develop a mapping from the JTA to the IOSSP [2].

The JTA is a forward-looking document. Each service area has two sections: a section for mandated standards and a section for emerging standards. The expectation is that standards in the emerging section will eventually move to the mandated section. The emerging standards section is based on inputs from the DOD community that participates in the update and review of different JTA versions, including Aerospace (through its customers, SMC and NRO). Several drafts of JTA Version 2 came out this year and we participated in their review. To place ourselves in a position where we can provide input to the JTA evolution that supports our customers' needs, we set out to investigate emerging standards in two areas: wireless internet standards and security standards. We identified two areas where wireless internet standards are being developed: (1) the Transmission Control Protocol (TCP) of the Satellite working group of the Internet Engineering Task Force (IETF), and (2) the Satellite Communications Protocol Standards (SCPS). We participated in meetings of the IETF and invited the principal SCPS engineer from The MITRE Corporation to give a SCPS presentation at Aerospace, in which representatives from most of our programs participated. SCPS is a suite of protocols that extend the internet protocols TCP, IP and FTP to operate in environments where signal reliability is low and signal delays are high, such as in satellite transmissions. An evaluation of the SCPS suite was conducted. It revealed that although SCPS is not directly interoperable with the current Internet protocols, it can be integrated with them via a fairly simple application gateway. A copy of a SCPS application gateway was obtained from MITRE and is currently being installed at Aerospace for evaluation and demonstration purposes. The SCPS protocols were added to the final draft of JTA Version 2 as emerging Internet standards. We also investigated standards for wireless computing and the security issues associated with wireless computing. We found that the most activity is in the areas of traffic analysis and key distribution when they are combined with mobile routing. Our initial results were documented in the form of a presentation.

The COE mandate requires C4I applications, including ground segments of our space programs, to be rearchitected using the operating system and middleware products from the COE, along with COE architecture rules. The COE architecture rules include guidance on how to configure applications to maximize their use of common middleware, a process also known as "segmentation," Human Computer Interface (HCI) guidance, and software quality guidance. We set up a COE lab to provide our customers with a testbed where they can bring their applications and assess the feasibility of making them COE-compliant. We installed COE on two platforms in standalone mode: Solaris 2.5 and NT 4.0, and used the installations to evaluate the COE segmentation and HCI guidance. We segmented the Satellite Orbit Analysis Program (SOAP), a satellite orbit simulation and visualization program developed at Aerospace, and segmented and rehosted on COE a mapping utility for a classified program. Additionally, we evaluated SOAP for its compliance with the COE HCI guidelines, and tested a beta version of a government-developed HCI evaluation tool developed for COE. The COE lab provided us valuable insight into the COE architecture process, which we shared with several programs, and documented in [3].

Our activities in support of COE evolution focused primarily on monitoring emerging products in the areas of security and distributed computing technologies and assessing how easy it will be to include them in future COE releases. We focused primarily on security products—in particular, the Fortezza migration. Fortezza is a symmetric key-based cryptographic module that supports communication security. The security features provided by Fortezza include encryption/decryption, secure hash, digital signature, and key exchange algorithms, and are implemented via a PCMCIA-compatible card. Fortezza standards are mandated in the JTA

for applications that need to interface with the Defense Message System (DMS); however, none of the current COE products support Fortezza. We succeeded in integrating a Fortezza-enabled browser (Fortezza-Netscape) and a Fortezza-enabled mail application (MS Outlook-Armormail) into the COE testbed. Additionally, because the distributed computing service product currently in the COE is the Distributed Computing Environment (DCE), which uses Kerberos for security authentication, we analyzed the differences between Fortezza and Kerberos, and investigated interoperability issues between the two authentication approaches. We identified the Generic Security Services Application Program Interface (GSS-API) as an enabling technology for migrating COE from Kerberos to Fortezza, since it can provide an interface between Kerberos-based applications and Fortezza-based ones. We began an evaluation of the security aspects of the emerging distributed computing standard CORBA, and found that initial specifications for two CORBA security levels have been released but no implementations exist for them yet. We participated in a number of COE working groups aimed at identifying new technologies for incorporation in future COE releases, and were invited to give a presentation about Fortezza-based Public Key Infrastructure at the COE Security Services Working Group.

We developed an infrastructure for disseminating the JTA/COE information accumulated on this project. Our information dissemination infrastructure consists of a Web page and a Lotus Notes database. We use the Web page to list all the standards in the JTA and to provide, for the major ones, summary information and hot links to their full text. The Lotus Notes database is used to store and index the JTA/COE documents we use, ranging from program artifacts (such as standards profiles) to acquisition guidance we developed (such as RFP guidance and migration plans guidance), and includes minutes from the various JTA and COE working groups that we attend.

In summary, the Joint Technical Architecture IR&D is experimenting with JTA standards and COE products and is investigating and developing innovative technologies that promote open system architectures consistent with the JTA and the DII COE. Next year, we will extend our COE testbed to encompass a fully networked client-server environment, and will add a database management component to it. We plan to add the capability to perform COE assessments in the area of software quality by purchasing the McCabe software metrics tools and integrating them into the COE testbed. The security aspect of JTA and COE will continue to be a focus of our investigation as it is the area least well addressed by the commercial sector. We will continue our exploration of CORBA security , and will complete and document our findings in the area of wireless security approaches and protocols. Additionally, we will maintain current versions of the COE in the testbed, and will continue to track COE evolution through our participation in the COE working groups.

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Environmental Technology

Upper Atmospheric Structure Effects

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This report covers results of the first year of an IR&D project whose objective is to better understand the highly-variable local density and temperature structure in the upper atmosphere, which can affect the performance of a wide variety of space systems. These structures appear in a variety of altitude regions. In the 80 to 100 km altitude region atmospheric gravity waves (AGWs), propagating upward from the lower atmosphere, break down and cause significant density and temperature perturbations. These perturbations can generate local turbulence that can propagate to higher altitudes and produce small-scale structure in the IR background emission. Above 100 km, space weather effects, such as the aurora, locally perturb the ionosphere and neutral atmosphere affecting communications, satellite drag, and background emissions. Missiles traversing the 80–300 km altitude region deposit plume wake chemicals that produce additional persistent IR clutter that is modulated by turbulent mixing and coupled to AGW-driven and auroral dynamic effects. In this report we discuss two important results of this first year: (1) our discovery that many of the small-scale (less than 50 km horizontal wavelength) AGWs are actually trapped in an atmospheric thermal duct and therefore can propagate many thousands of kilometers from their origin, and (2) the updating of an Aerospace Plume/Clutter Model using new laboratory data.

The Aerospace Nightglow Imager (ANI) is capable of obtaining images of the sky at night over a 60-degree field of view centered on the zenith. The main source of illumination is the OH Meinel airglow, which originates at an altitude of approximately 90 km. The brightness of this OH emission can be modulated by AGWs that pass through the layer, perturbing the density and temperature structure, which in turn affects the emission structure. Images taken when no AGWs are present appear uniform in brightness, while images taken when AGWs are present show highly-structured wavelike patterns of bright and dark regions. The modulation in brightness due to AGWs is on the order of 10 percent and a movie formed from sequential images shows the wave patterns moving. Thus, an examination of movies of images can reveal the percentage of frames where AGWs are present and the directions in which they are propagating.

From April 1995 to January 1996 the ANI was located in Adelaide, Australia [1]. During that time 1,858 OH images were obtained during 50 cloud-free nights. Using these data, both the fraction of time when waves were observed and their directionality were obtained using a simple wave-counting technique. The image was geographically divided into octants. If a discrete feature was seen to propagate between two successive frames this was counted as the presence of a wave on these two frames. The fraction of time that waves were present was calculated by dividing the total in each geographic direction by the total number of image frames for each period. These ratios therefore represented the fraction of time discrete spatially quasi-monochromatic (QM) features were seen to originate from a given direction.

Figure 1 shows the results for the entire period (4/95–1/96) and three periods centered around the winter solstice, spring equinox, and summer solstice. The plots show the percentage of frames where AGWs are seen to be propagating towards a given direction. The total number of frames for each interval and the percentage of the total where AGWs are observed are given to the side of each interval.

The main result of this analysis is that during the solstitial seasons, in particular, there is a very pronounced north-south anisotropy for the source direction of QM waves with a very strong seasonality. Around summer solstice, QM waves originate mainly from the north, while in the winter they originate from the south. The northern source is by far the stronger. The QM results for the spring equinox show an anisotropy favoring propagation from the southwest. The most likely explanation is that there is an anisotropy of wave sources. Since Adelaide is not located near a strong orographic feature, and there are no large orographic features north or south of the sites, it seems most likely that the source of the waves is weather-related storms.

First, consider that Adelaide is on the south coast of Australia. In the winter, storms originate in the South Polar Sea, south of Adelaide, and thus it is plausible that this is the source of QM waves seen travelling north in the winter. Furthermore, these storms could be close to Adelaide. However, in the summer there is a

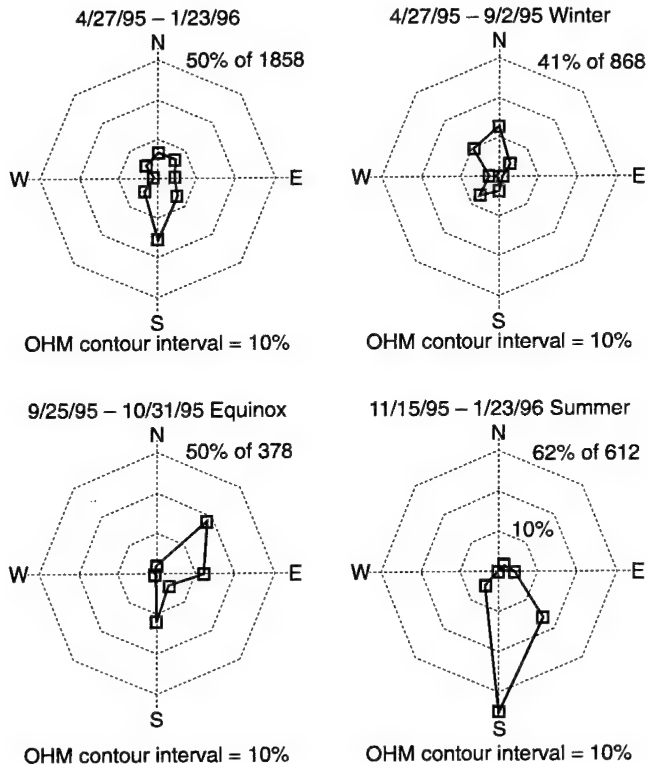

Figure 1. Contour plots of Atmospheric Gravity Wave directionality as measured by OH Meinel airglow (OHM) over Adelaide, Austrailia, for the entire 9 months of observation, and for three separate periods. Percentage of frames showning propagation in a given direction is plotted, out of the fraction of total observations in which AGW activity was detected.

problem. There is a strong source of QM waves north of Adelaide in late spring and summer; e.g., the large convection storm cells that occur over Darwin. But Darwin is over 3000 km north of Adelaide. Hines [2] has pointed out that short period, short horizontal wavelength waves must be located within a few hundred km in order to be seen over a site. Thus, how do these waves reach Adelaide? The central part of Australia, the region between Adelaide and Darwin, is the driest portion of the driest continent. There is no strong local source for waves close to and north of Adelaide in the summer.

If the AGWs are not locally produced, then there must be other mechanisms that allow long range propagation such as ducting (an analog to a waveguide or an electrical transmission line) in order to reach a distant site such as Adelaide. AGWs can be trapped by either thermal and/or wind shear (Doppler) ducts. A recent study [3] indicates that Doppler ducting may explain a significant fraction of the QM events seen in all-sky images. While Doppler ducting may certainly occur it seems unlikely to be the primary cause for the long range propagation of AGWs on a seasonal basis. For example, Doppler ducts, which depend on certain specific wind profiles, are likely to be short lived and localized.

The other possibility is a thermal duct. The mesopause forms the lower boundary of a lower thermospheric thermal duct that extends as high as 150 km. Thus the frequency of QM waves in the airglow should correlate with the height of the mesopause.

Winds can have an effect on the trapping ability of a thermal duct. Jones [4] was the first to examine this effect and found that waves propagating normal to the wind shear are most likely to propagate. Thus the directionality of ducted waves at a given location is governed by the location of wave sources and the wind direction.

During the winter months, the mesopause appears around 100 km while during the summer months the mesopause is at or below 85 km [5]. The *OH* airglow layer peaks below 90 km and has a full width at half maximum at or below 10 km [1]; thus during summer it is within the lower thermospheric thermal duct while during the winter it is below the duct. This, in combination with the location of the wave sources, would explain both prevalence and directionality of waves seen in our data. The analysis of the wind shear using a standard atmosphere to represent the winds also suggests that the Jones effect discussed above detunes the waves in the zonal direction while allowing waves to freely propagate in the meridional direction. Thus, north-south AGW propagation dominates because of a combination of the strong anisotropy of AGW sources and the Jones effect of the winds.

The reaction of fuel and oxidizer molecules in rocket plume trails with ambient oxygen atoms at altitudes above 80 km is a potential source of persistent IR clutter that is poorly understood and not previously addressed by plume models. Our objective is to improve missile surveillance and tracking capabilities by elucidating the chemistry and IR emission spectra of propellant reactions that can occur in cool missile wakes. The results of these laboratory measurements are incorporated into a mathematical model of the wake emission, which is then available as a tool for use in system design and evaluation.

We studied the chemiluminescent reactions of hydrocarbon propellants in a low-pressure flowtube. A dilute stream of fuel is introduced into the flowtube in the presence of excess atomic oxygen from a microwave discharge, and IR spectrometers are used to characterize the resulting chemiluminescent emission. During the past year, the measurements have been extended into the long-wavelength infrared (LWIR) spectral region with the use of two Aerospace-developed sensitive spectrometers employed normally for astronomical observations.

Figure 2 shows an emission spectrum from the *O*+butene reaction, collected with our Broadband Array Spectrograph System (BASS). Spectra have also been collected with an LWIR circular variable filter

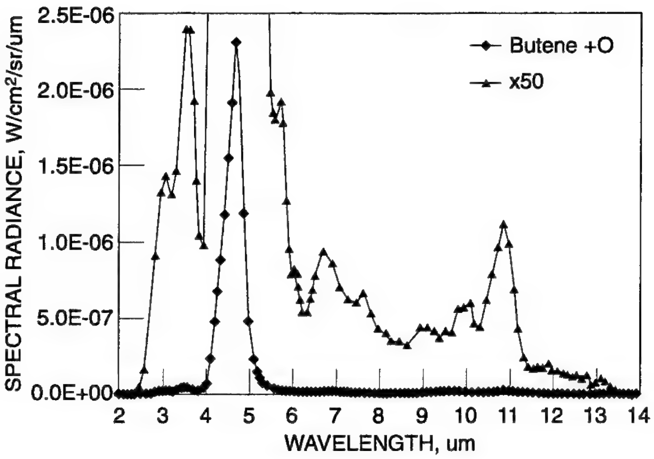

Figure 2. IR emission from the butene + oxygen atom reaction. This reaction, and others occuring in missile plumes, contribute to infrared clutter.

instrument and a high spectral resolution, short- to mid-wavelength FTIR spectrometer. Emissions from vibrationally excited *CO*, *OH*, and several other molecular species have been identified. The calibrated emission intensities are used to derive photon yields in different emission bands for use in a model of plume wake emission. Chemiluminescence spectra have been collected for a variety of hydrocarbon molecules, including acetylene, ethylene, butene, hexane, and toluene. Results from this laboratory study have contributed prominently to the conclusions and final report of a Ballistic Missile Defense Organization study group on persistent radiation from missile trails.

As part of this project, the Aerospace Plume/Atmosphere Chemiluminescent Clutter Model (PACCM) is being developed to describe the spectral, temporal, and spatial features of the IR emission generated in plume wakes under actual flight conditions. During the past year, the PACCM model has been upgraded with a detailed, temperature-dependent chemical mechanism for the combustion of hydrocarbon fuels with oxygen atoms. The mechanism is based on our laboratory observations of emitting species and photon yields and on a literature survey of chemical reaction rates. The mass and thermal transport elements of the PACCM model have been improved with temperature-dependent descriptions, and the effect of viscous heating on the propellant trail has also been modeled.

During the first year of this project, progress has been made in the interpretation of a variety of upper atmospheric phenomena. Specifically, during this year we have (1) shown that small scale AGWs can appear many thousands of kilometers away from their source, and (2) upgraded the PACCM model with a detailed, temperature-dependent chemical mechanism for the combustion of hydrocarbon fuels with oxygen atoms.

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Mesoscale Prediction and Toxic Dispersion

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Mesoscale meteorological models have cross-program applicability within a broad range of programs supported by Aerospace. The purpose of this IR&D program is to develop and improve a core capability in mesoscale meteorology with applications to plume dispersion, signal propagation, and improved use of satellite weather data. In addition, we have applied our existing upper atmosphere dynamic models to mesoscale phenomena in the upper atmosphere. The specific aims of this project are to: (1) establish a core capability in meteorological prediction at Aerospace, (2) characterize the atmospheric response to auroral energy inputs, and (3) investigate atmospheric disturbances caused by atmospheric gravity waves. The

major activities address requirements for: a capability in numerical weather prediction related to toxic dispersion from launches, tests and spills; the characterization of optical backgrounds for satellite surveillance systems; accurate orbital prediction for satellite ephemerides, collision avoidance and decay; and assessing atmospheric perturbations affecting re-entering vehicles. A predictive capability is also relevant to currently unsatisfied requirements of high-priority Air Force programs for the accurate specification of meteorological parameters. We have addressed the objectives of this project through the use of numerical models and data analyses. This report covers the activities of the first year of a three-year project. A summary of the results of our work in these areas during FY98 is given below.

The launch commit criteria used at Air Force ranges involve the prediction of the dispersion of the rocket plume and its toxic compounds. The present model used operationally on the ranges is a highly-simplified model that, when coupled with conservative exposure criteria, has led to costly launch delays. We have undertaken a comprehensive effort to improve dispersion models by integrating physical and empirical approaches to give better predictions of the drift, rise, and diffusion of plumes and taggants. Toxic plume prediction employs wind fields from a numerical weather prediction model to predict the bulk transport of toxins and a dispersion model to diffuse toxins relative to the bulk transport [1,2]. The primary meteorological model for this project is Mesoscale Model 5 (MM5), co-developed by Pennsylvania State University and the National Center for Atmospheric Research [3]. Toxic diffusion modeling via Lagrangian particle dispersion simulation has been implemented. This code has been run with measured winds and was used to simulate a Model Validation Program (MVP) plume release. It can also be easily modified to be driven by MM5 wind outputs. The full three-dimensional, time-dependent simulation can be displayed on a graphical workstation.

This model captures the standard operational practice in that it predicts an ensemble mean concentration, but not higher-order statistics. To provide more detail, we have developed a more advanced "spatially-correlated" Lagrangian particle dispersion model. Although computationally more intensive, the new model will allow the prediction of higher order statistics, such as concentration fluctuations and instantaneous peak concentrations. This model is currently being evaluated against existing models in the literature. The MM5 mesoscale model has been implemented on nested domains covering both launch ranges. The accurate prediction of toxin dispersion at these sites requires a reliable forecast of the land-sea breeze and the Planetary Boundary Layer (PBL) height. Both are known to be highly sensitive to the choice of PBL parameterization scheme. Model optimization is being evaluated by varying the model's PBL scheme, domain size, and grid spacing.

Three high-resolution schemes are being tested using the same initial conditions over the eastern range [4,5]. Grid spacing and domain size play off against each other. One must balance the need for computational tractability with the competing need to include enough information to provide the desired accuracy. A finer mesh grid necessitates smaller time steps and longer run times for a fixed domain size. One can decrease the domain size, but this limits the length of the forecast because spurious wave reflection at the model boundaries can rapidly contaminate the forecast if the model domain is too small. It was found that for the cases studied a domain size of 1100 km was adequate and that reductions in grid spacing below 3 km gave little forecast improvement. Model accuracy was determined by comparing model predictions of winds, temperature and humidity to balloon and tower measurements. The model has been exercised by applying it to simulate an actual instance of explosive cyclone development over warm water off Cape Canaveral.

We have developed a version of our model of upper atmospheric dynamics with a coordinate system that is suitable for intense localized heat sources such as Auroral surges. Auroral surges may be a very prolific source of gravity waves in the upper atmosphere [6]. As a means of validating the model, we have simulated the response of the Jovian atmosphere to the Shoemaker-Levy 9 cometary impacts. This work was an effort to reconcile discrepancies between earlier simulations of waves generated by the impacts and Hubble observations of expanding rings moving out from the impacts. The observed waves moved out much more slowly than predicted, leading to inferences of a wet stable layer that supported slow waves. This had far-reaching implications for the hydrogen-to-oxygen ratios in the Jovian atmosphere (implying ten times solar) and for theories of the formation of the Jovian atmosphere. We, on the other hand, were able to simulate waves with the observed speeds without the necessity of assuming ratios greater than solar [7,8].

Large-amplitude Atmospheric Gravity Waves (AGWs) propagating up from the lower atmosphere strongly perturb the altitude region where space vehicles reenter the sensible atmosphere and where minor species produce optical emissions [9]. The characterization of the perturbing effects of AGWs will help characterize the re-entry environment and optical clutter. In a collaboration with Clemson University we investigated the ducting properties of the upper atmosphere and found that winds can detune thermally ducted waves and thereby affect wave directionality (see below). We

also simulated the propagation of AGWs through wave backgrounds using kinematic wave theory in order to characterize the wave spectrum related to optical clutter. We have shown that assumptions used to derive wave spectra based on Doppler effects are incorrect [10]. We also performed simulations for a large number of AGWs propagating through different realizations of a background spectrum of waves, and have shown that the observed high-wavenumber tail of the spectrum can be explained by the effects of the time-dependency of the background wave field through which the AGWs propagate.

We have analyzed airglow data for the seasonal variation of the waves underlying the clutter spectrum; investigated the seasonal behavior of these waves (amplitude, direction, spectra), and correlated them with sources, the background wind, and thermal structure; and interpreted the observed waves in terms of thermally-ducted waves subject to wind effects [11]. We have extended our work on wave-driven airglow emissions to include the atomic oxygen transition radiating at 5577Å and originating in a layer centered near 97 km.. A spectral analysis of previously-acquired data for 14 nights from Arecibo Observatory, Puerto Rico revealed wave-driven fluctuations that suggest strong wave reflection related to ducting.

In summary, substantial progress has been made in all areas of this project. We have continued to develop computer models that simulate atmospheric disturbances and the chemistry relevant to wave-disturbed airglow. We have obtained and analyzed ground-based measurements of airglow to analyze wave disturbances in the atmosphere. We have identified improvements for an operational meteorological model used across a broad range of programs. Our modeling and analysis work has improved Aerospace's capability relative to meteorological simulation, toxic dispersal prediction, the characterization of optical clutter, drag prediction, and the characterization of the reentry environment.

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Surveillance Technology

Dual Use of Surveillance Satellites: Data Fusion and Analysis

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This report summarizes the results of research using the Defense Support System (DSP) for environmental monitoring purposes. The project goal is to address the need for a national and global remote sensing system for timely monitoring of natural disasters and other related phenomena. The globally-deployed DSP constellation provides a unique opportunity to detect such events and has capabilities that complement civil systems. Phenomena we have studied include wildfires, agricultural burning, volcanic eruptions and the spread of eruption ash clouds, and large meteor explosions in the atmosphere. To achieve the broad scientific and practical impact potentially possible, a systematic approach to gathering, ordering and studying the requisite data is being pursued. Active collaborations are in place with researchers from federal agencies, universities and private companies to gather and analyze all source data on natural hazards. The research results are being used to help guide a new disaster detection and mitigation program run by the United States Geological Survey (USGS) called the Hazard Support System.

The objectives of this project are: (1) to quantify the capabilities of various surveillance and meteorological satellites to detect and characterize transient events having both long- and short-term environmental consequences; (2) to study how the environmental observation data from multiple space sensors can be combined to realize the maximum benefit for potential users; (3) to construct and refine an Aerospace multi-satellite groundstation with accompanying hardware and software to identify and extract the relevant data in an automatic or semi-automatic mode; and (4) to cooperate with other agencies in data gathering and operational testing of this system for disaster mitigation and environmental monitoring purposes.

Major project accomplishments to date have included the following: (1) generation of case studies of numerous wildfires, earthquake-related gas fires, biomass burning in African savannas, widespread large fires in Mexico, volcanic eruptions and other phenomena; (2) data gathering and analysis of many cooperative wildfire field studies in Oregon, Idaho, New Mexico, Alaska, and Southern California, conducted with the U.S. Forest Service, the Bureau of Land Management, NOAA, the United States Geological Survey, the County of Los Angeles, and industry personnel; (3) upgrading Aerospace groundstation facilities to include NOAA GOES satellite reception and new automated 5m tracking dishes, so that geosynchronous meteorological imagery and DSP data can be combined live (this facility is referred to as the A-8 Research Facility, or ARC; (4) collaboration with Sandia National Laboratory Researchers to study meteor events and their infrared and optical signatures; (5) close cooperation in the development and test of the new Hazard Support System program, which is to be a government implementation of some of the remote sensing capabilities we have researched and demonstrated

Initial work on this project involved several key case studies chosen for their clear significance and the existence of good "ground truth". These case studies include the Los Angeles area wildfires, observables connected with the Northridge earthquake, volcanic eruptions in Mexico and Kamchatka, and several large meteor explosions. Among the most interesting and valuable early results were recorded DSP satellite observations of the Los Angeles wildfires, which occurred during the two-week period from 26 October through 7 November 1993. These data exhibited what we now understand as typical severe brush fire characteristics. This is characterized by an extended early "plateau" period followed by episodes of rapid, almost explosive growth. These data and those from the 1994 fire season were used to develop and refine automatic fire detection algorithms.

In more recent work we have participated in field tests to study satellite fire detection in cooperation with the U.S. Forest Service and Bureau of Land Management. These tests have been of two types: (1) monitoring of purposely lit prescribed fires by satellite and aircraft, and (2) so-called "blind tests" in which areas of the United States are monitored for fires on a 24 hour per day basis for 2 weeks followed by comparison of satellite vs. ground observer fire detection response

time. The prescribed burn results have demonstrated rapid space-based fire detection and helped to quantify satellite fire response capability through high resolution thermal data measured by specially-equipped aircraft. The blind test experiments have shown that space-based assets can detect some fires sooner than ground-based lookouts in remote areas. Data from the Gila National Forest in August, 1996 was statistically analyzed and a low false alarm rate was demonstrated. A follow-up helicopter survey revealed some supposed false alarms were actual undetected fires or gas flare targets. A report summarizing the unclassified weather satellite observations from this test was completed with NOAA, NASA, University of Colorado, and University of Wisconsin colleagues [1].

Another research area is investigation of the capability of the DSP system to monitor global biomass burning. Globally, biomass burning related to forest clearing for agriculture or seasonal grassland and crop stubble burning is a significant contributor to the global CO_2 budget. Habitat destruction and deforestation from this activity are other serious concerns. A recent effort to gather data from multiple spacecraft was a study of serious fires in Mexico in May, 1998. This fire activity threatened large tracts of the Chimalapas jungle in Oaxaca, one of the most biologically rich and diverse pockets of forest in Mesoamerica. Large jungle areas of Chiapas were also devastated. Figure 1 shows fire detections in Mexico and Guatemala during a 100-second period on 15 May 1998, near the peak of the fire activity. The data have been processed to group nearby fires into clumps. The DSP fire detections show comparable fire distributions to those derived from polar orbiting DMSP OLS and TIROS AVHRR sensors. Unlike those sensors, which sample an area only twice a day, the geosynchronous DSP satellites provide a continuous monitoring capability. These spring 1998 Central American fires occurred during the worst drought in the area in the last 70 years. Many occurred as a result of agricultural burning that got out of control and raged through the unusually dry jungle forests in Oaxaca and Chiapas. Over 2 million acres are estimated to have been consumed in Mexico, Guatemala, Honduras and Nicaragua. The U.S. Government contributed 75 Forest Service and State Department personnel and extensive air resources to aid in the Mexican Government's fire fighting efforts. During this last El Niño year, the U.S. Government has assisted Indonesia, Malaysia, and Brazil, as well as Mexico, during similar periods of uncontrollable wildfire outbreaks. The data pictured in Figure 1 and other material were briefed to USGS, Forest Service, and State Department personnel as an example of what types of information the Hazard Support System could provide in the future to assist in detecting and monitoring serious widespread fires of this type. The timely monitoring provided by combining the capabilities of diverse satellite systems can be expected to assist with these efforts in the future.

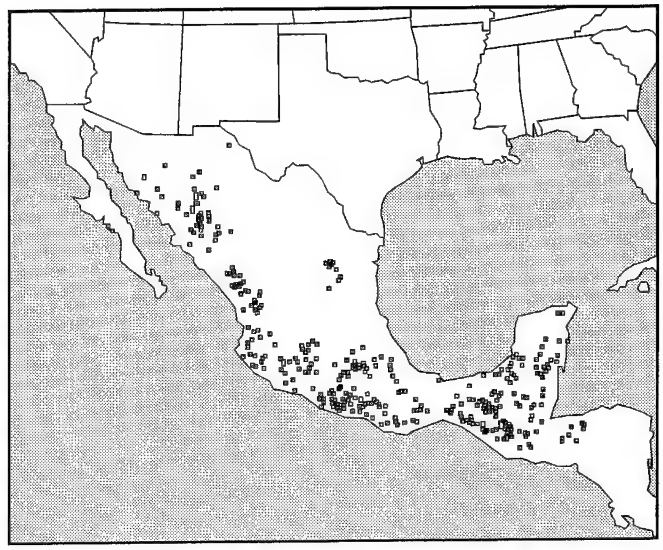

Figure 1. Widespread fire activity in Mexico and Guatemala on 15 May 1998, 21:45 GMT. Several hundred individual fires were visible.

Progress to date has allowed Aerospace to become an important contributor to efforts at the national level on the application of classified and unclassified satellite assets to disaster warning and mitigation and environmental crisis monitoring. We are continuing to work with agencies such as the US Geological Survey, US Forest Service, Bureau of Land Management, Sandia National Laboratories, and other federal agencies. We are now deeply involved in overseeing and assisting in the creation of the Hazard Support System to be housed at the USGS Advanced Systems Center in Reston, Virginia. The satellite ground station infrastructure constructed during this project will continue to support natural disaster-related remote sensing research and development in support of this effort and will help ensure that the USGS is able to achieve its goals for fire and volcanic activity detection and reporting.

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Civil, Commercial, and International Remote Sensing: Technology & Applications

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This report covers progress made during the second year of an IR&D project whose objectives are to survey, categorize, and critically compare the characteristics of burgeoning civil, commercial, and international (CCI) space-based remote sensing systems, sensors, and products. Such systems will proliferate dramatically in the coming decade, and by 2001 the number of countries owning such systems is expected to be 2.5 times the 1995 level (see Figure 1). Complex, expensive government and military systems are decreasing, while hybrid government/commercial and fully commercial systems, as well as smallsat-based systems (see Figure 2), are increasing. The US government requires an accurate forecast of technologies and capabilities in the CCI arena in order to exploit, rather than duplicate, these systems. The Aerospace Corporation and its customers understand that CCI sources of space-based remote sensing expertise and data may represent the best available solution to certain US problems. For instance, imagery from the French SPOT system is now outselling imagery from the US Landsat system, the US has no SAR (Synthetic Aperture Radar) comparable to the Canadian RADARSAT, and the highest-resolution, commercially-available imagery now comes from the Indian IRS-1C and 1D systems and the Russian SPIN-2 system, with resolutions of 5.8 meters and 2 meters, respectively. The situation is poised to become much more complex, as Argentina, Australia, Brazil, Chile, Germany, Israel, Italy, Malaysia, Pakistan, South Africa, South Korea, Spain, Taiwan and Thailand all acquire spaceborne remote sensing systems (and indeed, Chile and Thailand now have their first simple systems in orbit). The imminent launch of the first US commercial high-resolution (sub-meter resolution)

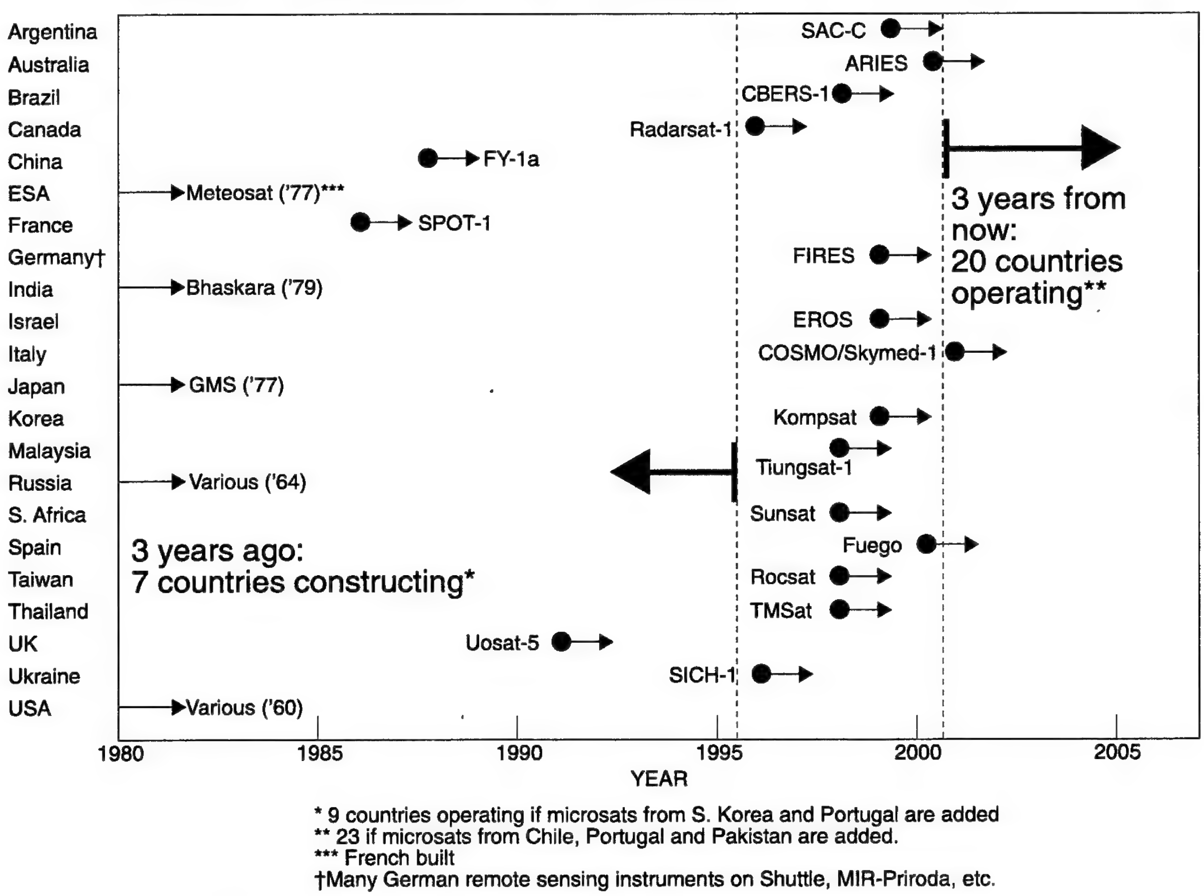

Figure 1. Remote sensing at the crossroads: countries fielding free-flying remote sensing satellite/sensor systems 1980–2007.

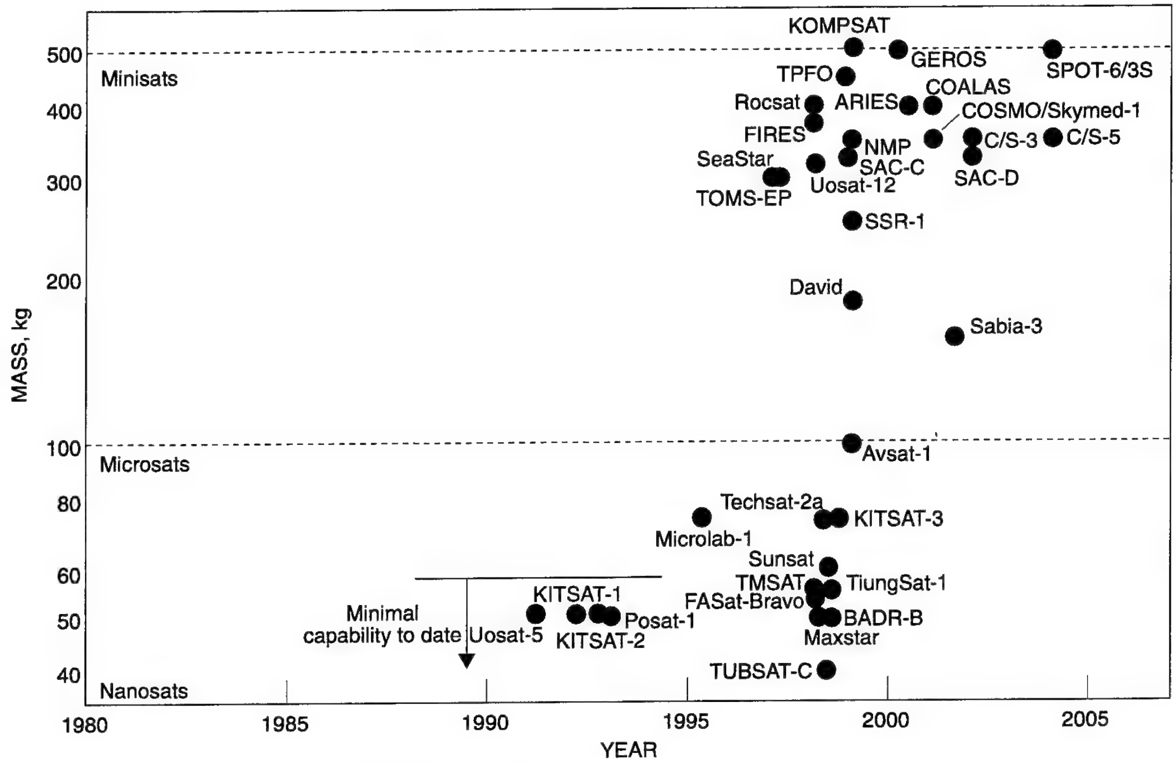

Figure 2. Proliferation of small satellites for Earth observation 1980–2007.

systems poses many opportunities to potentially dominate the world market, but it also raises concerns about security and technology transfer. This field is on the cusp of tremendous change, and a comprehensive look at its history, its status, and its future is quite timely.

Aerospace has completed a survey of the past, present, and future programs of 23 countries—from Argentina to Ukraine. Those programs have been categorized in terms of multispectral and hyperspectral bands (see Figure 3), high resolution, stereo visible, ocean color, SAR, smallsats, hybrid government/commercial, and fully commercial programs. They have been identified and quantified in terms of the technical trends in these areas. Also completed is the development of a pilot relational database employing a simple graphical user interface, which will become available to Aerospace and appropriate government entities in FY99. Benchmarks and metrics that characterize these systems and sensors have been developed, and the ability to rake those benchmarks and metrics across the database in order to identify all of those systems and sensors that may have applicability to a given problem has been demonstrated. In terms of products, a study of the evolution and future of the geospatial data processing field has been completed, with an emphasis on geographical information systems (GIS). GIS allows a user to overlay remote sensing imagery with natural and manmade ground and infrastructure information, such as county and state boundaries, roadways, rivers, wetland boundaries, pipelines, etc.

Under this effort a pilot data set of imagery from selected CCI systems was built. A test site in Camarillo, California was chosen, and digital spaceborne panchromatic, multispectral, and SAR imagery, as well as digital airborne hyperspectral imagery, were acquired. High-resolution (sub-meter) airborne color film imagery of the test area was also acquired to serve as the background or "base" layer in the GIS analysis. The imagery has been georectified; i.e., geometrically adjusted to conform to a standard reference frame, and all of the images have been coregistered, so that each image lies accurately on top of the next. The ground and infrastructure GIS data for this test area were acquired and coregistered with the imagery. To round out the pilot data set, the Russian SPIN-2 satellite, a former surveillance satellite turned to commercial uses and producing two-meter resolution imagery from film, was tasked to image the area; however, it was clouded out. Because these satellites last a maximum of 45 days and are currently launched infrequently, the next opportunity for a data collection will be in FY99. In support of this attempted collection, the Corporation's capability to collect ground truth information was improved, principally through acquisition of, and experience with, large deployable calibration targets.

An assessment of the image quality of the pilot data set and an initial assessment of its military utility were performed. This data set is already finding other uses in support of corporate customers, and is expected to have

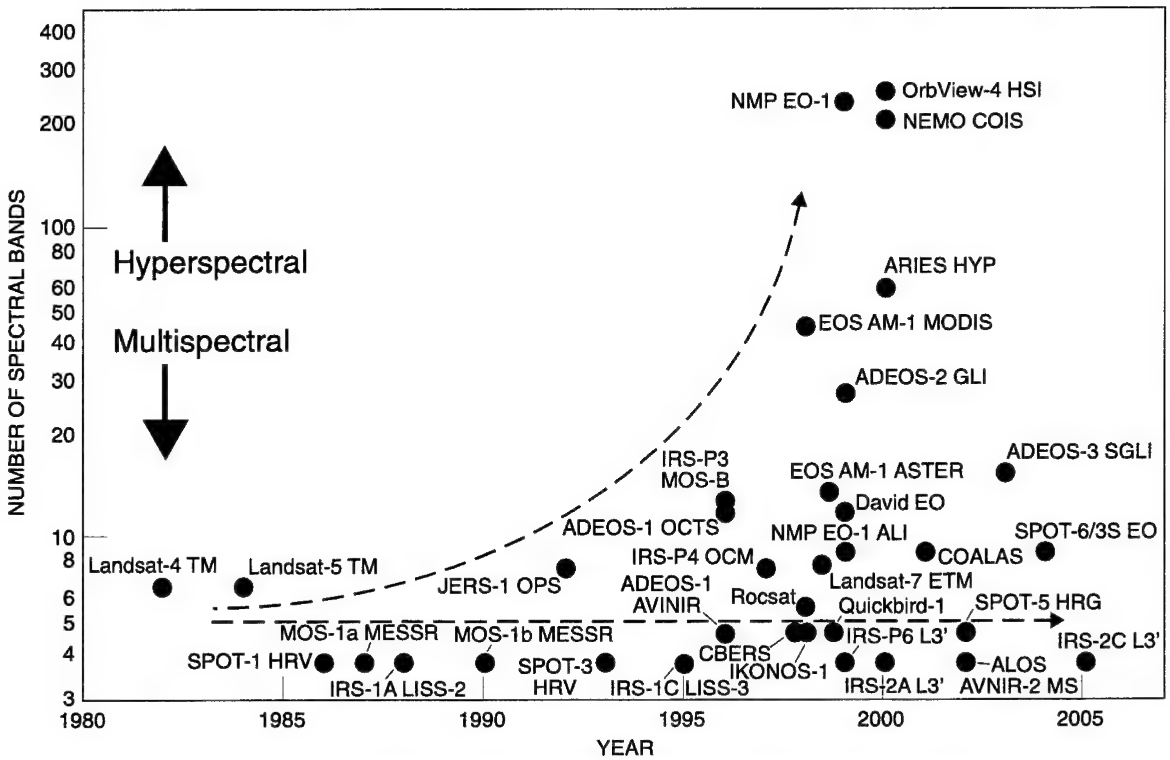

Figure 3. Diverging trends in spectral bands for civil spaceborne visible/IR imaging instruments 1980–2007.

broad applicability as its existence becomes more widely known. We plan to expand the data set significantly under FY99 IR&D funding as new systems are launched, which will make it even more valuable.

One goal for FY98 that was not accomplished was the acquisition and analysis of the first high-resolution "one-meter" commercial imagery. This occurred because the field of commercial remote sensing got off to an inauspicious start, as EarlyBird-1 from EarthWatch, Inc. failed on orbit due to a faulty GPS unit that drained its power, the TRW/NASA Lewis mission failed on orbit due to an unexplained attitude control problem, EROS-A from West Indian Space failed on launch, and the launches of the first one-meter resolution systems were postponed into FY99 (following repeated assertions that they would not be). As a result, no digital, high-resolution commercial imagery could be added to our image set in FY98. A goal of the FY99 IR&D effort is to rectify that situation with the collection of imagery from the IKONOS-1 satellite of Space Imaging, and the tasking of the next SPIN-2.

The principal goals for FY99 are: (1) to acquire, register, and assess more types of imagery, including the Russian SPIN-2, the Aerospace SEBASS (thermal hyperspectral), and US commercial one-meter imagery; (2) to fully populate and update the database of systems and sensors, advertise the database, and make it generally available within Aerospace and to appropriate government entities; (3) to issue an Aerospace Technical Report summarizing this three-year IR&D project; and (4) to secure funding sources for long-term maintenance of the database.

Issues in Remote Sensing

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Space and Environment Technology Center

This project takes advantage of our unique capabilities in remote sensing and computational modeling of our field measurements to advance our basic understanding of atmospheric aerosols. This year we concentrated on two fundamental aspects of noctilucent clouds (NLCs): the size and composition of their particles.

Noctilucent clouds (NLCs) are the highest clouds in the Earth's atmosphere, occurring typically between 80 and 85 km at latitudes above 55° during the polar summer. The NLCs are a potential source of clutter in some remote sensing systems. They are most clearly seen after sunset when the lower atmosphere is no longer

illuminated by the sun, but the NLCs are still in full sunlight. At these high latitudes the sun only dips a few degrees below the horizon during the summer months, which makes it possible to view such clouds throughout the night.

We have developed a ground-based technique that relies on measuring the polarization of scattered sunlight from NLCs using HIROIG, an ultraviolet spectrograph developed in the Space and Environment Technology Center. We first demonstrated this technique in 1995 when measurements were made from the National Science Foundation's Sondre Stromfjord observation site in Greenland. We determined that the particle radii in those NLCs were 70 nm or less [1]. While that size range was in agreement with the few other previous NLC particle size measurements taken, there was uncertainty regarding the results. Because these initial measurements were carried out with the sun only 4 degrees below the hard Earth horizon, there was a high background from solar scattering in the troposphere. As a result, NLC particle scattering was only about 1 percent of the total observed signal. In 1997 and 1998 we made new measurements with the sun 7 degrees below the horizon, providing much lower background conditions. Preliminary results based on analysis of these measurements are discussed below.

The HIROIG instrument is a CCD-based spectrograph that measures the entire 270 to 370 nm spectrum at 1 nm resolution in one of three polarization angles. By obtaining spectra at all three polarization angles (0, 45, and 90 degrees) we can determine the intensity and degree of polarization of light entering HIROIG. For this experiment HIROIG was placed at the Sondre Stromfjord site at 67° north, 304° east for two weeks in early August of both 1997 and 1998. HIROIG was pointed in the zenith and was mounted on a tripod that could be rotated so that the entrance slit could be kept aligned with the azimuth towards the sun. This procedure was followed to maintain a constant geometry for polarization effects from scattering of the solar radiation by the cloud particles. Four spectra—the three polarization angles and one dark spectrum taken with the shutter closed—were obtained every 5 minutes from about sunset to sunrise. Simultaneous with the HIROIG measurements being taken, a lidar system monitored the zenith for the presence of NLCs.

A typical plot of the degree of polarization of scattered solar light from the troposphere is shown in the upper panel of Figure 1. There were no NLCs present on this night according to the lidar data and the sky was also very clear and free from tropospheric clouds. The degree of polarization reaches its maximum shortly after sunset at a value of 67 percent. This value is influenced by multiple scattering effects that occur at this wavelength of 377 nm. The polarization reaches its minimum around local solar midnight (3.5 Universal Time (UT)) and then begins to increase. On this day (7 August 1997) the maximum solar depression angle was about 6.5 degrees. The fluctuations in the polarization around 3.5 UT are due to the low intensity of the scattered solar light, which results in a decrease in the signal-to-noise ratio.

In contrast to 7 August 1997, the early morning hours of 10 August 1998 had an intense NLC display that began around 2.5 UT and continued into sunrise. According to the lidar results, the NLC altitude was around 82 km and the intensity of the backscattered lidar signal from the cloud increased noticeably after 4 UT. The shape of the polarization curve resembles that from 7 August 1997 until about 4 UT. However, after that time there is a large increase in the polarization due to light scattered from the NLC particles. The shape of this polarization increase appears to indicate that the NLC was most intense around 4.5 UT. However, the lidar data suggests that after that time the NLC did not decrease in intensity; rather, the shape of the NLC polarization bump is due to the fact that after 4.5 UT the background solar scattering is becoming increasingly dominant in the total measured signal. Note that in 1998 the maximum solar depression angle was between 7 and 8 degrees.

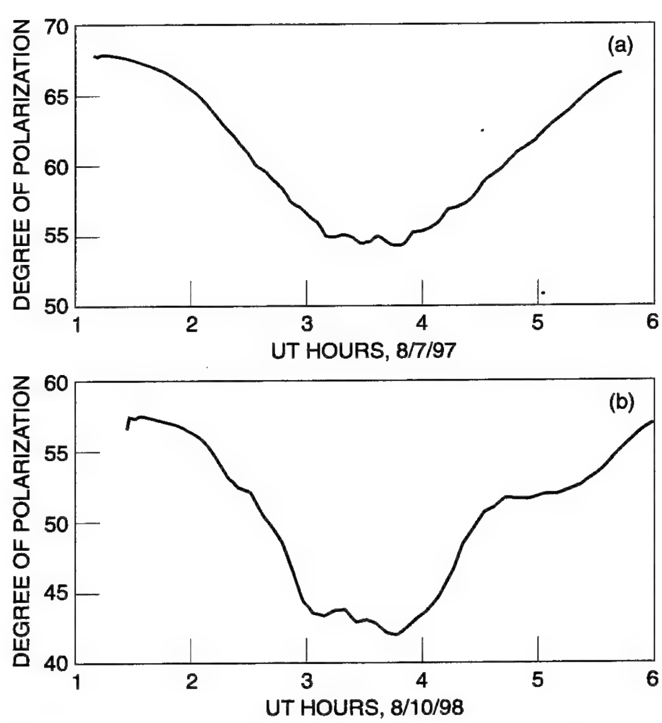

Figure 1. (a) Degree of polarization, as a function of Universal Time, of the zenith sky over Sondre Stromfjord on August 7, 1997. (b) Same as (a) but for August 10, 1998. Notice the large polarization excess at around 4.6 hours on the lower panel. This is clear evidence of NLCs and relates directly to the size of the particles.

The discussion in ref. [1] provides a method of retrieving particle size from these data. In addition to the polarization one needs the fraction of the total signal intensity due to the NLC particles. For this display that fraction reached nearly 40 percent at 4.5 UT. Given this, one can determine a polarization due to the NLC particles of near 65 percent, which implies a particle size near 110 nm. These are preliminary results and it is expected that during the next year we can obtain a more definitive answer by looking at data from other wavelengths, including the available lidar data. Nevertheless, it appears that NLC particles were larger than normal for this display and this could have some implications for the clutter they could induce in certain space-based remote sensing systems.

Most scientists believe that NLCs are made of water ice. This is based on indirect evidence, including arguments concerning the stratospheric water budget, the detection of molecules that could be photodissociation products of ice, etc. Yet no one has actually detected water ice directly. We believe that the 3.1 μm vibration band of *OH* in the ice lattice could unambiguously determine whether ice is present or not. The feature is strong in ordinary cirrus clouds, and falls in an atmospheric window that allows the NLC to be observed from the ground. A spectrum taken in 1975 by Harrison [2] shows the feature, although he did not recognize it in his spectrum as being due to ice.

We, however, did recognize the feature. To quantify the identification, we began modeling the spectrum using various radiation codes and computational techniques (see below) and a number of different dielectric functions, some based on previous IR&D work [3,4]. The results seem to indicate that Harrison's earlier noisy spectrum did indeed show the ice band. We are presently refining our computations and making plans for a field campaign to actually measure the line shape with high signal-to-noise ratio.

Two studies relating to the modeling of NLCs were carried out this year. The first extended our work from FY97 on the scattering of electromagnetic waves from heterogeneous materials. This issue is important because many of the natural objects that reflect, scatter, and emit radiation measured by remote sensing instruments are heterogeneous; e.g., snow, sea ice, soil and vegetation. NLCs are thought to be mostly water ice, but optical spectroscopy and in situ stratospheric measurements suggest that significant impurities may be present, primarily hydrated sulfates.

Last year we developed an exact theory of scattering from a model spherical heterogeneous particle. Upon completion of this work, we realized that the exact solutions that were derived for this problem could be used as the basis for a new effective media theory, which we developed this year. Effective media theories are based on the assumption that the optical properties of a heterogeneous medium can be described by an effective dielectric constant. The best known of these are the Maxwell-Garnet and the Bruggeman theories [5]. The theory we developed is entirely new, but has some interesting complementary relationships to the Bruggeman theory (see Figure 2). Our new theory and its relation to the other theories was included in a larger paper that also covered the work performed last year [6].

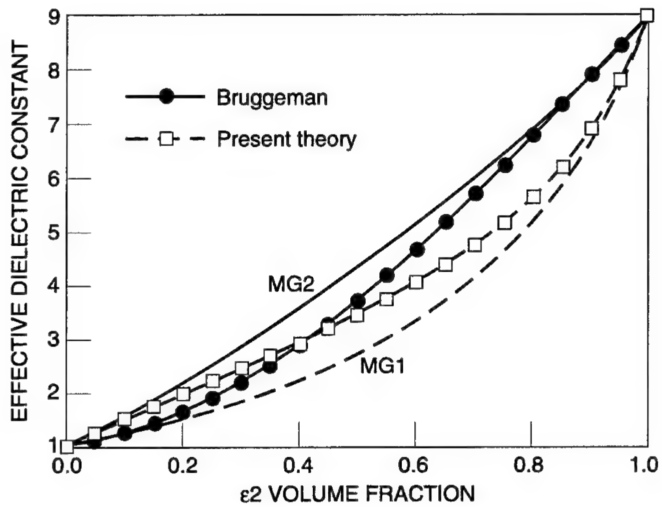

Figure 2. The curves are the effective dielectric constants of a two-component heterogeneous mixture, where $\varepsilon_1 = 1$ and $\varepsilon_2 = 9$, versus the volume fraction of ε_2. The four curves are calculated by the two Maxwell-Garnett approximations, MG1 and MG2; the Bruggeman approximation; and the new approximation based on exact theory that was derived in the present work.

The second study was an effort to develop efficient new computer algorithms to calculate scattering and emission properties of nonspherical particles (e.g., ice particles in cirrus clouds and noctilucent clouds). Good approximation methods exist for calculating scattering from such particles that are small compared to the radiation wavelength and also for particles that are much larger than a wavelength. Unfortunately, there is a gap between these two methods that requires solutions of the wave equation that are very computer-intensive. In many cases the particles are randomly oriented and the radiation is not polarized. Our proposal for these cases was to simplify the problem by an approximation that replaces the full electromagnetic wave equation by a simpler scalar wave equation. Efficient methods developed to solve atomic scattering problems could then be used to solve the scalar wave equation. This year, we tested our scalar wave approximation on simple problems for which accurate, exact solutions could be calculated. The initial test was a comparison with Mie theory. This test showed that for particles whose radius is larger than a wavelength, the scalar approximation is remarkably accurate. With this success, a computer program to calculate scalar wave scattering from simple

nonspherical particles was developed. At present the program is operational, but we have not yet had a chance to compare these solutions to exact solutions to the electromagnetic wave equation.

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Infrared Spectral/Spatial Instrumentation and Measurements

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Space and Environment Technology Center

This project utilizes a variety of infrared instrumentation designed and developed in-house to make IR measurements of target signatures and backgrounds. The measurements are designed to support architecture studies, signature evaluation, on-orbit calibration of IR sensors, and astronomical and aeronomical research. By working with state-of-the-art instrumentation, we broaden our expertise in hardware and analysis techniques, thus permitting us to better support our SMC/NRO/NASA customers. This program provides a hardware-based approach to hands-on remote sensing that has led to publishable scientific results as well as new business and recognition in the scientific and technical communities.

In past efforts we began to develop and use near-IR cameras and spectrographs that employ the same types of two-dimensional *HgCdTe* arrays that are in use on the Hubble Space Telescope and will be used in USAF surveillance programs. In the thermal IR (3–14 μm), work has begun on an LWIR imager using an array from the Space Based Infrared Systems (SBIRS) program, while the Broadband Array Spectrograph System (BASS) has turned its enhanced accuracy and sensitivity to laboratory flame studies, the space threat of meteoroids, and the development of the capability to provide timely reference stellar spectra for variable stars that can be used for on-orbit IR sensor calibrations. This report presents a few of the new scientific results and the directions in which the program is currently moving by focusing on the individual instruments that are at the heart of the overall effort.

The Near Infrared Imaging Spectrograph (NIRIS) is a grating-based imaging spectrograph currently employing two 256 × 128 *HgCdTe* arrays. The overall spectral range is 0.8 to 2.5 μm, which is covered by two channels, referred to as the shortwave and longwave channels. As an imaging spectrograph NIRIS produces a so-called data cube that specifies both the spectral and spatial characteristics of the observed scene. To gain experience with very large, ultra-sensitive *HgCdTe* arrays, we are obtaining a 1024 × 256 device to incorporate into NIRIS. This array design is optimized for low background, faint source observations. It will double the spectral and spatial resolution and double the spectral coverage. To accommodate the increased data rate and the lower read noise, a new set of generic array electronics that will be applied to this and at least three of our other 2D array-based IR sensors has been designed and is currently being fabricated for use in FY99.

In the past year NIRIS was used to observe sources from the 2MASS Survey (an all-sky survey at 1.25, 1.65, and 2.2 μm that includes objects more than 10,000 times fainter than the 2.2 micron survey of 30 years ago), several small moons of the outer planets, asteroids, active galaxies and quasars, and novae and supernovae. Spectroscopy of so-called symbiotic novae (binary systems including a white dwarf and a giant star) is the topic of our most recent paper. Figure 1 shows a spectrum obtained for 2MASS 1516 +19, a distant active galaxy that was first discovered in the infrared. This galaxy is thought to have a large black hole at its center, similar to the one believed to be present in our own galaxy. Note in particular the very peculiar shape of the underlying continuum. For comparison, the spectrum of our sun would be declining monotonically as λ^{-4}. The rise at longer wavelengths is probably due to emissions from very hot dust. Because the dust absorbs the initial radiation from the

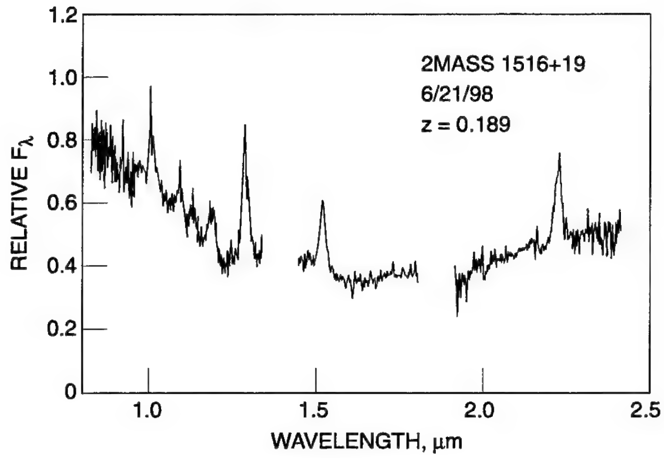

Figure 1. A spectrum obtained by the NIRIS instrument of an active galaxy from the 2MASS sky survey. Most of the lines in the spectrum are from the Paschen series of Hydrogen; Pa a and Pa b are at 2.2 and 1.5 mm, respectively. The strongest feature is He I l10830. The redshift, z, of 0.189 for this object corresponds to a look-back time of more than a billion years. Data is missing at wavelengths of strong absorption in the Earth's atmosphere.

core and reradiates it at a reduced temperature, the presence of the dust in the galaxy skews the energy distribution from the fundamental processes that radiate primarily in the ultraviolet and visible into the infrared. This in turn warps our view of the overall energetics in the universe based on optical studies where such energetic objects as this are frequently missed.

The Near-Infrared Camera (NIC) is a mature instrument and efforts to improve its performance have concentrated on increasing the rate at which data can be read out and stored. This is particularly important to our program of *speckle* observations. Speckle studies attempt to recover diffraction-limited images representative of sources above the atmosphere by limiting exposure times to intervals sufficiently short so that distortion due to atmospheric turbulence is essentially frozen. Currently the integration time is typically 0.1 second, but the time required to store the resultant data can run up to 1.5 seconds, resulting in very low duty cycles. The camera also has an alternate configuration providing a broader field of view that was used at the Wyoming Infrared Observatory (WIRO) operated by the University of Wyoming for approximately 6 weeks of observing this year. That time will increase in FY99 as our collaboration to provide a facility instrument for WIRO grows. In the past year the Wyoming collaboration resulted in two publications (see Bibliography) and the dissertation work of two students. For the WIRO work, the NIC was used primarily for measurements of filamentary dark clouds, photometry of novae, and photometry of cataclysmic variables, which are very short-period binary stars that include a white dwarf as one of the pair of stars.

Work in the thermal IR (3–14 µm) included exploitation of the Broadband Array Spectrograph System (BASS) and further enhancement of the Mid-IR Imaging Spectrograph (MIRIS), a large-field (~.5 × 12 degree) slitless spectrograph that uses an InSb 256 × 256 array and operates in the 2–5.2 µm region.

The BASS was used at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea to measure the first-ever infrared spectrum of comet 55P/Tempel-Tuttle, the parent body of the Leonid meteoroids. Unlike the dozen or so such spectra we have obtained over the years on other comets, comet Tempel-Tuttle shows a smooth, featureless blackbody-like spectrum with no trace of the silicate emission that we commonly see in other comets. In order to understand this, we developed an approach to retrieving particle size and composition based on a first-principles analysis of energy balance for a dust particle in space. The results strongly suggest that the dust particles in comet Tempel-Tuttle are much larger than those normally found in comets and most probably are composed of a mixture of silicate and carbonaceous grains. This work will be extended to help determine the composition and temperature of the meteoroid dust in order to better characterize the threat of Leonid storm meteoroids to orbiting spacecraft.

BASS attempted spectra of several Perseid meteors during their August appearance, another first for this spectral range and a critical step as a proof of concept for our proposed program to study the Leonids during their reappearance in November 1998 and 1999, when large meteoroid fluxes are expected. MIRIS was also operated during the much weaker Perseid shower in August of 1997 (when a meteor was seen), and in its enhanced mode—but without a detection—in August of 1998. This demonstrated the probabilistic nature of any attempt to study meteors, and the value of operating these sensors during a meteor storm such as the 1998 and 1999 Leonid appearances when the zenith hourly rate of meteors is expected to be enhanced by a factor of 1000 or more over typical shower fluxes. These observations have also required us to develop new software and observation procedures to efficiently observe and then reduce the massive amounts of data produced.

This spectrographic capability has led to a NASA-funded contract with the SETI Institute to fly these two sensors on the Flying Infrared Signature Target Aircraft (FISTA) in order to measure the Leonids from a location over Okinawa. This is an optimal geographic location for the 1998 storm. The aircraft will carry the sensors above most of the earth's atmosphere as part of the SETI-developed collaborative effort to simultaneously study the Leonids with a wide variety of sensors.

The heavy schedule for use of the BASS has led us to develop a second instrument. Operations at different

sites have in the past required us to make internal changes to adapt internal optics to various telescopes, which entails both risk and downtime for the instrument. With dual instruments we will be able to dedicate one BASS to SBIRS-related work, largely conducted at the Mount Lemmon Infrared Observatory in Arizona. The second instrument will also provide a backup for critical BASS observing missions. The new instrument is almost complete and we expect it to become operational very early in FY99.

The IRTF observations included observations to characterize emissions at two longitudes on the surface of Mercury. Earlier data from the NASA Kuiper Airborne Observatory obtained by the NASA ARC IR group had suggested that a new, strong feature was present near 5 microns. Our data showed no such feature, at least at the two longitudes we studied. Features indicative of the surface material in the 8–12 μm region were verified, in spite of the fact that the data had to be collected on days when clouds were intermittently above the observatory. The spectrographic nature of the BASS, combined with its high sensitivity, permitted good spectra to be taken in time periods only a few minutes long, and new software was developed to recognize and extract the good data from that contaminated by clouds.

The IRTF runs also contributed observations of 15 of the bright, irregular IR variable stars that can be used as on-orbit calibrators. Additional stars were observed from Mt. Lemmon with the BASS in September 1998. The observing program will continue through the on-orbit testing of the SBIRS-Low demonstration satellites, and could be used for the operational SBIRS satellites. This will provide a cross-program calibration, as the stars used for DSP (Defense Support Program) satellite characterization are included.

Finally, the capabilities developed under this program have resulted in strong support for the SBIRS program in such areas as filter manufacture and test, calibration planning and sensor testing, and on-orbit planning. To further this application of our hardware experience to the SBIRS programs, we have coordinated with the program office to obtain a Long-wavelength Low-background Uniform Mosiac array that we will install in our 10 μm Aerospace Camera (AIR-CAM). Given the time and funding constraints on the array program, the contractors have not had the opportunity themselves to explore the operation of the arrays in detail. We expect that our hands-on experience with the same arrays used on-orbit will result in better support for optimization of on-orbit operation and anomaly resolution during the orbital phase of the SBIRS flight demonstration program.

Systems Engineering

Costs of Space, Launch, and Ground Systems

S. A. Book, L. B. Sidor, H. S. Shim, and M. S. Alvarez
System Development and Operations Subdivision

The primary objective of this continuing IR&D project since it was begun in FY87 has been to update, enhance, and document in easily usable form the corporate knowledge base of historical and contemporary space-system costs, including costs of satellite, launch, and (for the first time in FY97) ground systems. The documentation, in the form of briefing charts and facing-page text, has been updated approximately every two years since 1987; the most recent edition (the seventh) of "Costs of Space, Launch, and Ground Systems" appeared in April 1997. FY98 was a data-gathering year; the next edition is scheduled to appear during the summer of 1999. Virtually all cost data contained in the report is contractor-proprietary, and cannot be disclosed outside the US Government/FFRDC network.

The original FY87 study, initiated by C.L. Whitehair at the request of the Board of Trustees' Ad-hoc Committee on Cost, was a pioneering effort that contributed significantly to fulfilling an identified critical need on the part of the government's system-acquisition community to understand the costs of existing space systems. With the benefit of hindsight, we now realize that the Board of Trustees' request was a brilliant flash of foresight, because the end of the constant military threat environment of the Cold War in 1991 led to a significant reduction in funding for military space systems and a more careful investigation by the government into the costs of proposed new systems. The research conducted over the years as part of this IR&D project has placed Aerospace at the forefront of knowledge of costs of space-related systems. Now more than ever before, cost is considered by both military and civilian government space branches as a performance criterion ("cost as an independent variable," "faster, cheaper, better") equal in importance to all other performance criteria. Data gathered and analyzed in the course of this research effort has been used to support source-selection efforts and as guidelines for reducing costs of future space systems. The need for an acquaintance with cost issues will grow more significant as larger numbers of Aerospace personnel become involved in the commercial arena, where the relationship between the producer's cost and the customer's concept of value is the primary driver of sales.

As noted above, this year was a data-gathering year. In addition to updating the existing data on costs of large and small Air Force and NASA satellites and the standard launch vehicles, new data was gathered on the International Space Station, launch facilities (including launch pads and supporting structures) at Vandenberg and Cape Canaveral, and a wide variety of ground systems. In addition, some information on expenditures for technology development at the USAF Phillips Laboratory has been obtained.

IR&D funding supported the principal investigator's service on NASA's Cost Assessment and Validation Task Force for the International Space Station ("Chabrow Committee") for a six-month period during which NASA's budget and expenditures were thoroughly investigated [1]. These data are now available at Aerospace and will be studied and organized for distribution during the FY99 phase of the project. Other investigators accumulated cost and specification data on assembly buildings, processing facilities, control centers, and launch pads at the east and west coast launch sites. Finally, IR&D funds supported cooperation with The MITRE Corporation on joint development of a ground-systems cost model to support Air Force needs. Data gathered in support of model development will be organized for presentation in the next edition of "Costs of Space, Launch, and Ground Systems."

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Systems Engineering Tools for Mission Performance and Utility Analysis

This IR&D effort had two thrusts: (1) the development of methods, tools, and a team to analyze space system mission effectiveness and conceptual design (the FRAME task), and (2) warfare modeling research, with emphasis on cause-and-effect relationships in combat models and simulations. These two subtasks are reported separately below.

Space System Mission Effectiveness and Conceptual Design—FRAME

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Systems Engineering Division

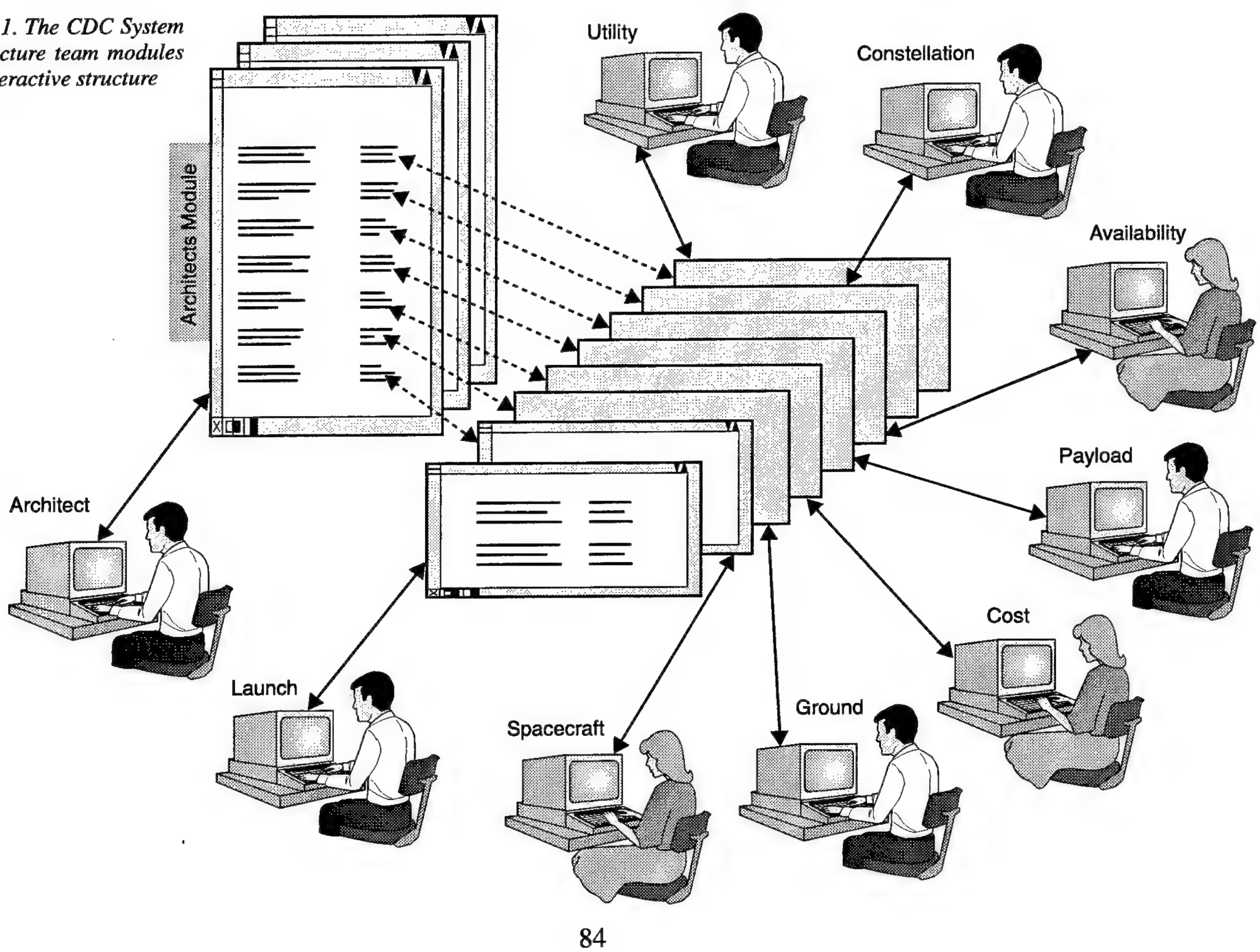
The objective of this project is to develop mission-level space architecture analyses and evaluation tools and methodologies. Work in previous years has produced a number of products that demonstrated the feasibility of a system analysis toolbox for developing space-system architecture models and analyses. Besides the spreadsheet tool prototype modules, procedures for utilizing these modules were also developed. The totality of procedures and modules is referred to as FRAME (Functional Requirements Analysis of Mission Effectiveness).

The FRAME product was integrated and merged as a part of the Concept Design Center (CDC) IR&D activities this year. It was recognized that the FRAME methodology, tool set, and team approach had much in common with the CDC capabilities that have been developed under separate IR&D funding. The CDC consists of a hierarchy of architecture design and analysis segments, including the original Space Segment capability (spacecraft focus), this newly-created Space Architecture segment (space system focus—formerly FRAME), and newly-emerging mission architecture, ground, payload, and launch segments.

The CDC Space Architecture structure is depicted in Figure 1. Principal design and analysis modules include the architect's seat (study coordinator), mission utility, constellation design, constellation availability, payload design, spacecraft design, launch and ground segment support, and space system life-cycle cost estimation. The analysts who sit at these functional positions interact during an analysis session to provide evaluations of, and iterations on, space system candidate architecture designs. These evaluations produce mission utility and space system life-cycle costs for each candidate architecture. The iterative, interactive nature of analysts acting together provides concept evaluation and modification in a real-time environment, thus shortening study timelines and focusing resource usage.

The CDC Space Architecture team, in cooperation with the Systems Planning and Engineering Group, conducted a study of a Hyper-Spectral Imaging (HSI)

Figure 1. The CDC System Architecture team modules and interactive structure



space system in support of theater warfare. This study was a subset of a larger Commercial Architecture Study (CAS), since commercial space systems were considered for HSI data relay. The HSI system produces large volumes of sensor data, for which wideband communication alternatives are needed to relay the information to theater users. A study of HSI systems with varying levels of Ground Sample Diameter (GSD) pixel footprint resolution and communication linkage alternatives, including Teledesic, Celestri, and TDRS relay systems, was conducted. The utility to the warfighter was evaluated as the days of conflict duration progressed, and the architecture cost included HSI development, production, and operation, as well as communication relay leasing costs. Results of this study were documented for the program [1].

This year's activities conclude a most successful IR&D effort. The FRAME IR&D study has successfully transitioned from a research effort to a recognized engineering capability, and a valuable active program support resource.

Warfare Modeling Research

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D. Y. Buitrago and R. H. Weber
Strategic Awareness and Planning Directorate

This report covers progress made during the second year of a continuing IR&D project whose objectives are to improve the fidelity and clarity of cause-and-effect mechanisms in warfare models and simulations, and to gain insight into efficient means for incorporating these mechanisms into both quick-reaction campaign models such as SEAS (System Effectiveness Analysis Simulation, an in-house tool) and the larger, campaign-level combat models such as NSS (Naval Simulation System), and J-WARS (Joint Warfare Simulation). We have observed, as have others [e.g., 2, 3, 4], that current warfare models and simulations still suffer from many problems in the areas of model transparency and traceability to cause-and-effect. For example, according to [2], "Contemporary combat models are not based on firmly established laws whose proper application is well understood.... As a result, today's models are ad hoc and opportunistic. They lack generality and their validity is seriously questioned for good reasons.... The combat models embedded in them are not credible...."

Thus we have developed an experimental warfare modeling simulation testbed that allows us to experiment with and test assumptions, model subsets, and strategies and tactics before incorporation into campaign-level simulations. The essential foundations for this testbed are a previously-developed conceptual structure and associated data model for warfare modeling, as these provide a unifying, clarifying, and simplifying influence on all of the subsequent model and simulation development. The current implementation of our experimental warfare modeling testbed includes (or will soon include) all of the top-level categories of our conceptual structure: ISR (intelligence, surveillance, and reconnaissance), communications, data processing and exploitation, strategy and tactics, concept of operations (OPS concept), firing and attrition, logistics, scenario, and environment.

A unique element of this approach is the capability to model both discrete (e.g., sensor updates, report arrivals) and continuous (e.g., motion through space and time) processes and to keep them properly synchronized. This is accomplished by using a numerical differential equation solver (which has a special test for checking and updating engagements and the event queue at each time step) to keep discrete and continuous processes in synchronization.

The main idea here is that, unlike in physics, where motion results from interplay of forces and inertia, in warfare modeling motion results primarily from decisions. These decisions are based on the results of ISR, communications, and processing, and how these outputs interact with the various decision processes (i.e., strategy, tactics, OPS concept). The equations for target motion can be derived from the continuity equation for target densities, assuming that the target densities are sums of delta functions. The right-hand sides of these equations are the forcing functions that contain the effects of the various decision processes at work, and represent the desired (or commanded) movement, whereas the left-hand sides represent the individual targets' attempts to conform to these decisions. On the other hand, weapon allocation decisions (i.e., whom to fire at next) can take a variety of weapon, sensor, target, and OPS concept criteria into account. We are investigating a variety of approaches to decision modeling, as it is probably the most complex part of warfare modeling, and can have a major impact on simulation outcomes. Decision modeling is currently a very active area of research worldwide, and some of the approaches we are currently investigating include

neurodynamic stochastic programming, neuro-fuzzy controllers, complex adaptive systems, and various types of autonomous agents.

The development of this experimental simulation testbed would have been virtually impossible without the kind of powerful, flexible interactive computing, graphics and documentation capabilities that the *Mathematica*® computation environment provides. The entire simulation is currently just a few hundred lines of code. A status report on this work [5] was presented at the MORS (Military Operations Research Society) Annual Symposium in Monterey, California in June 1998, and at present an initial version of the simulation has been completed and is being debugged.

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Concept Design Center

A. B. Dawdy, G. W. Law, and J. A. Aguilar
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The Concept Design Center (CDC) was created as part of the FY97 IR&D program. Since then, the CDC has evolved from a single team of engineering experts focused on spacecraft design to a collection of teams emphasizing a range of capabilities from detailed sensor design to space system architecture analysis.

The CDC has proven to be an efficient way to organize the cross-discipline conceptual design and analysis capabilities of The Aerospace Corporation. Programs utilize the CDC for conceptual design and analysis problems requiring extensive cross-discipline interaction. The CDC does not replace traditional engineering support to Program Offices, but offers an alternative approach to rapidly organize and manage cross-discipline conceptual design teams.

The CDC is (1) a team that draws on the breadth of the Corporation's engineering expertise; (2) a facility where the Program Office and customer can interact efficiently with the team of experts; and (3) a process for applying innovative design tools to produce quality results rapidly. These three elements yield an engineering analysis product with greater detail and consistency, produced more rapidly and at lower cost than traditional systems engineering studies. This enhances the effectiveness and productivity of the Corporation's system architects.

CDC teams have been developed for different product lines of space-system/architecture design and analysis: system architecture, space segment, ground systems, and electro-optical payload. Each of the CDC teams is drawn from across the corporation and encompasses a broad range of expertise.

The System Architecture Team (SAT) focuses on system architecture trades for a single space system involving changes to constellation, payload performance, and concept of operations. SAT products are estimates of the life cycle cost and military utility for each architecture option evaluated. Constellation performance and system availability are key analyses, with top-level spacecraft size estimation and ground facility estimates provided for cost estimation. Figure 1 presents a block diagram of the SAT team; each box represents the function and Aerospace organization that contributes personnel, expertise, and tools to accomplish the team's tasks.

The Space Segment Team (SST) focuses on conceptual spacecraft designs and trade studies for understanding cost versus requirements and technical feasibility issues. Team members represent each spacecraft subsystem and the ground segment. SST products include detailed conceptual spacecraft designs in addition to top-level ground segment and system software sizing required for costing

The Ground Segment Team (GST) focuses on command and control, mission processing, and dissemination architectures. The team identifies the system-level

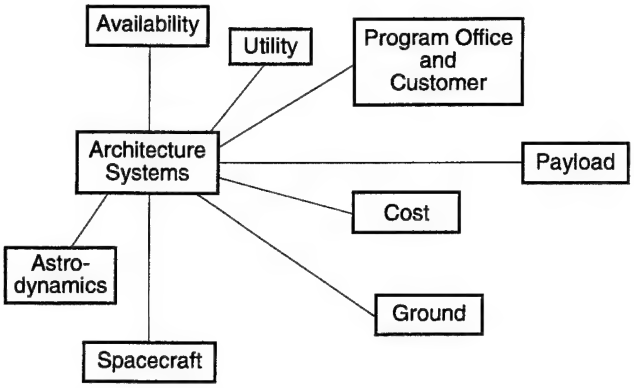

Figure 1. System Architecture Team. Feedback from hardware, cost and facilities teams can point out weaknesses in architecture designs, and assure robust system concepts.

elements—staffing, processors, communication links, information architecture, software and facilities. Top-level spacecraft and payload performance are estimated to understand their impact on the ground segment. GST products include conceptual design-level architecture descriptions and life cycle cost estimates for each element.

The Electro-Optical Payload Team (EOPT) focuses on conceptual designs of electro-optical sensor payloads. EOPT products include detailed performance and hardware designs for sensor elements such as focal plane, optics, thermal control, structures and mechanisms, and attitude control. High level estimates of spacecraft bus characteristics are included to determine payload constraints. Relative sensor costs are also estimated.

CDC teams are designed for the easy transition of studies and information across the different teams. The same individual may participate in different teams at different levels of detail, enhancing continuity and the flow of information. Figure 2 shows organizational participation across the CDC teams.

A CDC team member represents his/her organization's specialized expertise. Team members develop and maintain their modules used in the CDC environment and train other individuals from their organization in the module's use.

Several new CDC teams are currently under development. In addition to the GST, a new Mission Architecture Team (MAT) will extend the CDC's capabilities further into the architecting arena. Additional payload teams have also been proposed, including a Communications Payload Team that would focus on the design and analysis of military and commercial communications systems. CDC is also influencing reusable launch vehicle design processes through our relationship with the Reusable Launch Vehicle CRI.

The facility utilized for these types of realtime, interactive design activities has several important characteristics. The entire team and the customer need to be co-located during the design process. This allows for face-to-face contact and encourages discussion. During design sessions, multiple simultaneous conversations often take place as each team member works to understand their requirements and the impact their products will have on others. The facility must provide access to the teams' tools and information sources in a way that does not hamper effective inter-personal communication.

Two facilities have been prepared specifically for the conduct of CDC activities. The CDC Facility, in Building A1, provides an environment dedicated to this type of realtime interactive design activity. The facility is equipped with 15 NT workstations and a network fileserver for use by the CDC teams. Large screen projectors help focus group activities and enhance understanding.

The A5 Backplane Computer Facility (ABCf), located in Building A5, has been jointly developed by the Air Force and The Aerospace Corporation. The conduct of CDC activities in this facility was specifically taken into account during its design and outfitting. Between the CDC Facility and the ABCf , the CDC now has the necessary resources to effectively perform studies for a broad range of customers.

This fiscal year has seen the CDC mature from an IR&D activity to a significant corporate capability. Eleven customer-funded CDC studies have been completed in FY98. At the end of FY98, six studies are currently in progress, and five more studies are in the early planning stages. Customer response to this new capability has been exceptionally positive and demand continues to grow.

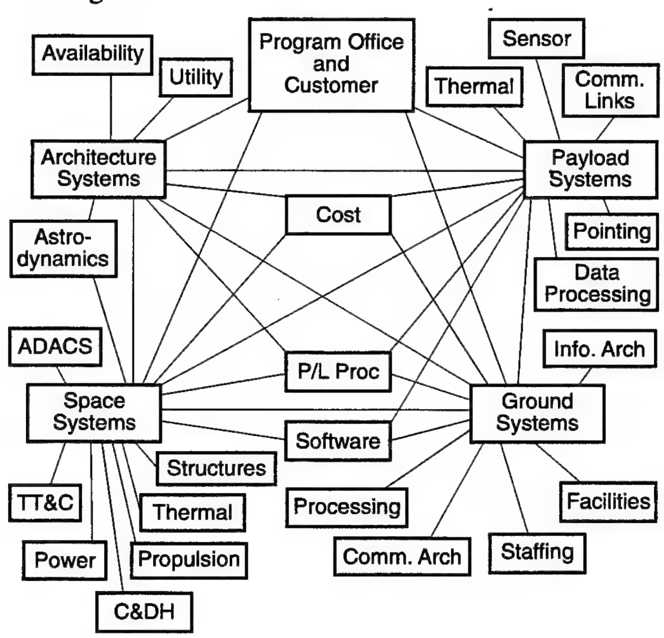

Figure 2. CDC Participant Interactions. Additional expert teams for major systems and hardware functions are developed as required by growing customer demands.

Much of this success is due to the IR&D efforts that support the development of the new CDC teams and enhance existing capabilities. The System Architecture Team was formed by integrating the FRAME activity being developed under the "Systems Engineering Tools for Mission Performance and Utility Analyses" IR&D project. Both IR&D activities contributed to the tool modifications, process development, and training required to support the SAT.

The Electro-Optical Payload Team, developed primarily under customer funding, also was successfully integrated into the CDC team structure. This new team has rapidly developed a broad customer base beyond its initial sponsor.

Ground Segment Team development planning and research was initiated as part of a mid-year increase to IR&D funding. The GST presents many new challenges. The need to concurrently develop conceptual designs for each ground architecture element while characterizing interdependencies requires the development of new techniques, processes, and tools that will be the focus of a significant portion of FY99 activities. The flexibility to address the broad range of future ground systems while maintaining an acceptable level of fidelity and detail are a primary concern in this effort.

Evolving the CDC processes and techniques to accommodate tasks of vastly different scope was also investigated this year. We explored the possibility of applying the CDC approach to applications such as system-of-systems architectures, mission area architectures, and policy level decision making. The potential application of the CDC's methodologies for group interaction, inter-module communication, and data transfer for these higher-level architectures appears very attractive, and is a major thrust in next year's activities.

Significant advances were made in the capabilities of many of the original Space Segment Team tools. Enhancement of the software sizing module was a significant achievement this year. Research and development in this field has yielded a new capability for defining the functionality, size and cost of future software development efforts based on system characteristics, complexity, and concept of operations. This unique capability was presented by Aerospace at this year's Ground System Architecture Working Group (GSAW98) and the USC Center for Software Engineering's Focused Workshop on Software Engineering and System Engineering. An invited briefing to the 13th International Forum on COCOMO and Software Cost Modeling was presented in October, 1998.

A new solid modeling capability has been prototyped for inclusion in the CDC Space Segment Team. An additional team member is being added to the SST who will develop a graphical representation of the design during the design session. Computer hardware and software were acquired to facilitate this new capability. Training and database development were also accomplished this year in preparation for implementation in early FY99.

A new staffing estimation model has been developed to support both the SST and the GST. It provides a framework for experienced ground segment engineers to estimate the staffing levels required at different nodes in a ground architecture based on system characteristics, historical staffing data, the functions performed, the concept of operations, and technology projections.

The spacecraft thermal subsystem module was significantly updated. Research into historical spacecraft characteristics and advanced technologies was incorporated into a design tool that allows thermal engineering specialists to develop conceptual estimates based on the mission and the characteristics of the other spacecraft subsystems.

Continued visibility into the evolving CDC capabilities is critical to its success. To maintain a base of proficient personnel capable of leading and performing CDC activities, it is necessary to continually educate both customers and new team members in the CDC tools, techniques and processes. In support of this goal, a technical paper was prepared and presented at the 8th Annual International Symposium of the International Council on Systems Engineering (INCOSE). A short video describing the CDC and demonstrating a design session has been produced and is being distributed to both internal and external customers. A User's Guide has also been prepared that will help educate customers in the capabilities of the CDC and describes how to effectively utilize the CDC.

The Concept Design Center has had an exceptional year. It has been widely adopted by our customer and has a much larger engineering staff, which actively contributes to its success. The next year promises to continue these trends as its scope expands further to meet the needs of an even larger customer base.

Advanced Technologies for Space Systems

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Systems Engineering Division

This report provides an overview of new advancements in space hardware and systems. The information presented here was gathered from commercial and government agencies as well as an extensive literature search. Emphasis was placed on commercially-available hardware that has recently become available or will be available within the next 5 years. The goal of this research is to provide the necessary background information for the evaluation of space system concepts incorporating new technologies in their design. This first-year effort is a useful starting point for a more detailed inquiry into space hardware technology readiness.

Current spacecraft bus systems can be grouped into three size categories: large (dry mass >500 kg), small (500 kg >dry mass >50 kg), and micro (dry mass <50 kg). Large satellites typically have a longer design life (about 10 years), a large degree of redundancy (often dual string), and higher cost. Large satellites are trending toward higher power, such as the new 15 kW Hughes HS702. Small satellites typically have a simpler design with shorter design lives (about 2 years), single string or selected redundancy, and lower cost. A general trend among small satellites is toward higher performance. Improvements in pointing accuracy (<0.1 deg), for example, will enable higher resolution remote sensing using small satellites. A relatively recent development in the space industry is the emergence of microsatellites. Typically simple from a functional standpoint, microsatellites are highly integrated in their design and are often characterized by low power consumption (which allows for body-mounted solar panels), passive stabilization, and little or no on-board processing. Current microsatellite manufacturers include AeroAstro (Bitsy) and Surrey Satellites UK (UoSAT, PoSAT, and others).

One common trend for all bus classes is the reuse of common hardware to reduce schedule and cost. The Hughes HS 601, for example, has been used for applications as diverse as the UHF Follow-On for the DOD, the NASA TDRS relay satellite, the next generation NOAA GOES weather satellite, and commercial communications satellites such as the Galaxy series for PanAmSat. When the payload requirements (i.e., pointing accuracy, payload power) differ significantly from the typical application, however, the cost and time necessary for modifications can be substantial.

Some of the most dramatic improvements in space hardware appear to be in power, electronics, and computing components. The commercial electronics and computing industry has pushed the state of the art in the areas of integrated circuits and power systems, which has enabled significant mass and power reductions for space applications.

Developments in attitude determination and control hardware have occurred in attitude sensors such as star trackers. The Ball CT 602 star tracker, for example, achieved a 28 percent mass reduction and 17 percent power reduction through redesign of the CT-601 star tracker [1]. More dramatic future developments are discussed in recent literature with mass projections as low as 0.5 kg for new lightweight star trackers [2,3,4]. These miniaturized star trackers will allow higher accuracy pointing for small satellites. There is also considerable work being done on GPS applications for attitude determination. The GPS Attitude and Navigation Experiment (GANE), which flew on the Shuttle in May 1996, provided attitude knowledge to within 0.3 degree (3 sigma) per axis and attitude rates to within 0.01 deg/sec (3 sigma) per axis at 0.5 Hz.

Substantial improvements have been made in the areas of data processing and storage. Current solid state recorders achieve capacities of up to 512 Gbits at rates of about 1 Gbps [5]. Improvements in space computers have benefited from progress in commercial computing. The current state of the art in space computing is typified by RAD6000-based processors. Increased data handling capacity will further facilitate a move toward payloads that provide a larger data volume, such as high resolution and hyperspectral imagery.

With the widespread commercial use of spaceborne RF communications, there have been incremental improvements in solid state power amplifiers and transmitters. These improvements are based on developments in application-specific integrated circuits (ASICs) and monolithic microwave integrated circuits (MMICs) [6]. It is projected that amplifier efficiencies will improve from about 35 percent to 50 percent over the next few years.

A significant advancement in space communications will be the realization of optical communications, which utilize pulsed lasers to transmit signals. The system includes a laser (the transmitter), a telescope with optical detector (the receiver), and a pointing system to align communication nodes. The new commercial Teledesic system (scheduled to begin service in 2003) is planning to use laser communications for crosslinking at 1.2 Gbps [7].

Current Gallium Arsenide/Germanium (*GaAs/Ge*) solar cells have efficiencies of about 18–19 percent. One method of increasing efficiency is by growing

different layers of photovoltaic material into an integrated stack of cells (also called multi-junction solar cells). Spectrolab has developed a dual stack cell that has a 24.2 percent efficiency [8], while Phillips Laboratory's Space Power and Thermal Management Division has created a Gallium Indium Phosphide/Gallium Arsenide/Germanium (*GaInP/GaAs/Ge*) triple-junction cell with a 27.6 percent efficiency. Dual-junction solar cells were first flown when the PAS-5 satellite was launched in September 1997. Both major manufacturers of space-qualified solar cells, Applied Solar Energy Corporation and Spectrolab (Hughes), are selling new dual-junction and triple-junction solar cells that provide efficiencies ranging from 20–24 percent.

Lithium-ion batteries will provide significant mass reductions and should be available in the near future. These batteries currently have a life span of only about 1000 to 2000 charge/discharge cycles, but have several advantages over current nickel-cadmium and nickel-hydrogen batteries. Lithium-ion batteries are half the weight of a nickel-hydrogen battery, for example. The recharge efficiency of lithium batteries is also better. Current batteries convert 80 percent of the charge energy to discharge energy while lithium batteries convert 90 percent of the charge energy. Since lithium batteries do not contain ferro-magnetic metal (i.e., nickel) they can be used in satellites carrying sensitive magnetometers. Lithium batteries, however, cannot sustain an overcharge. Overcharging a lithium battery will either damage it or lead to bursting. A small 7 *Ah* prototype lithium cell was recently developed and now the Europeans are developing a 40–100 *Ah* cell suitable for telecommunication satellites for flight aboard the technology demonstration satellite Stentor in 2000. A 24 *Ah* lithium battery was planned for use on the Deep Space 1 spacecraft; however, two nickel-hydrogen batteries were used instead [9].

Advances in materials are making the use of flywheels on satellites feasible. The International Space Station will test a set of flywheels and may eventually replace batteries with flywheels to reduce operational costs. An advantage with flywheels may be combining the power storage and the attitude control wheels into one system. The USAF and NASA are sponsoring the FASTPAC (Flywheel Advanced System Test for Power and Attitude Control) program, which is developing a single wheel flywheel system having a 3 kW-hr storage capability, a high specific energy, and a life span of about 10 years. The program is scheduled for completion in 1998 and will be followed by a dual-wheel flywheel program that will combine both power storage and attitude control functions.

New advances in propulsion include higher efficiency chemical propellants and thruster systems and new concepts in solar electric propulsion (SEP). The advances in chemical propulsion will provide modest improvements in specific impulse. TRW, for example, is producing a new line of advanced thruster systems for dual-mode (Hydrazine/N_2O_4) chemical propulsion systems including the Advanced Dual Mode Engine (ADMLAE) and the SCAT attitude thrusters [10]. Advances in electrical propulsion provide options for dramatically improved performance if the disadvantages of large power requirements (several kilowatts), system complexity, low thrust, and increased complexity in low thrust trajectories can be accommodated. The NSTAR xenon electric thruster was launched on NASA's DS-1 mission in November 1998, while Hughes is preparing its Xenon Ion Propulsion System (XIPS) for its HS702 bus.

One advancement in the area of thermal control is the application of aerogel thermal insulation, which provides a very low thermal conductivity at a very low weight (its density is approximately three times that of air). Recently, aerogel was used to insulate the Mars Sojourner rover. NASA's Lewis Research Center is currently developing cryogenic electronics that can operate at low ambient temperatures in deep space, which would eliminate some of the heating systems presently used.

Significant advancements in the area of inflatable structures have been made in recent years. Large inflatable structures have been developed by L'Garde to support a 3-meter antenna experiment flown on the Space Shuttle in 1996. NASA's New Millennium program is examining the use of inflatable structures for space-based radar applications and lightweight rovers. New concepts for inflatables include the injection of a liquid curing agent used to add rigidity to the structure once inflated.

Many significant advancements in space hardware development have been prompted by advances in the commercial sector and government research such as NASA's New Millennium Program. Lightweight, efficient electronics have enabled improvements in the areas of data processing and storage, power, communications, and attitude sensing. These improvements may ultimately enable higher performance spacecraft at lower weights and costs, paving the way for new space applications.

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Abstracts

Brief abstracts of Independent Research and Development projects undertaken in FY 1998 are presented below. For additional details on any of the projects, please contact the authors.

Corporate Research Initiatives

Microtechnology for Space Systems

S. Feuerstein, S. Amimoto, H. Helvajian, S. Janson and B. Weiller
Mechanics and Materials Technology Center

J. Osborn
Electronics Technology Center

L. Kumar
Vehicle Systems Division

L. Gurevich
Systems Engineering Division

With the advent of microtechnology, mechanical/electronic device miniaturization to the submillimeter scale is becoming a reality. MEMS (microelectromechanical systems) technology offers significant advantages in achieving batch-processed, low cost, lightweight reliable devices for terrestrial as well as space applications. The Aerospace Corporation has focused on the development and insertion of MEMS into military space systems. The effort, established as a Corporate Research Initiative in FY96, is comprised of four tasks. Accomplishments in each task element for this year are as follows:

- Task 1: MEMS Wireless Multiparameter Sensor (MPS) Development. Advancements were made in MPS technology demonstration, electronic hardware, software, and chemical sensor development as well as Delta-Graphite Epoxy Motor (GEM) casing MPS functional demonstrations.
- Task 2: Global Positioning System (GPS)/MEMS Inertial Measurement Unit (IMU) Demonstration. A GPS/IMU magnetometer testbed was developed. Fusion algorithms were formulated and MEMS gyros evaluated. GPS/MEMS IMU system performance was determined in ground tests.
- Task 3: Micropropulsion Technology Development. Laser microfabrication capabilities involving arrays of silicon, glass and ceramic structures were significantly improved. Micro ion engine and micro resistojet components were fabricated.
- Task 4: Development of a Nanosatellite Space System Design Methodology. An integrated approach was developed and experts in the required disciplines carried out a preliminary evaluation of essential design requirements.

Exploitation of Commercial Microelectronics for Space Applications

B. K. Janousek, R. Lacoe, S. Moss, J. Osborn and D. Mayer
Electronics Technology Center

S. Crain
Space Environment Technology Center

N. Sramek and J. Culliney
Electronic Systems Division

A Corporate Research Initiative was begun in FY96 to identify and demonstrate approaches for incorporation of commercial microelectronics technology into space systems while maintaining adequate levels of radiation tolerance and reliability. To accomplish this objective, work was carried out on several interrelated tasks with the following results: (1) the Aerospace laser simulation facility was used to evaluate the single event latchup behavior of commercial application-specific integrated circuits and analog-to-digital converters; (2) the Aerospace RADCELL test chip has been fabricated at several commercial foundries and was used to demonstrate design techniques for reducing susceptibility to single event latchup; (3) the total dose hardness of commercial CMOS processes was evaluated, and at least one commercial foundry was identified that produces radiation-tolerant ICs; (4) a methodology for the rapid prototyping of radiation-hardened circuits using a commercial foundry was demonstrated that should result in improved procurement practices for future space missions; and (5) Aerospace participated in two flight testbeds that will serve to verify the on-orbit performance of commercial microelectronics.

Airborne Hyperspectral Imager (AHI)

J. A. Hackwell
Office of Spectral Applications
P. H. Lew
Space Environment Technology Center

The objective of this program is to establish a facility for collecting and analyzing infrared hyperspectral remotely-sensed data taken with the Spectrally Enhanced Broadband Array Spectrograph System (SEBASS) sensor. Since its first use in October 1995, SEBASS has been employed in over a dozen field campaigns to explore the utility of infrared hyperspectral techniques for detecting and characterizing gas plumes, for locating and identifying camouflaged targets both day and night, for surface material identification, for mineral exploration, and for studies of atmospheric compensation techniques. This year, we met all four of our goals: First, to finish the development of the "Spectral Exploitation using Automated Logic" (SEAL) Version 1.0, a software application that is designed for automated processing of SEBASS data. Second, to adapt our atmospheric compensation algorithm to meet SEAL interface specifications. Third, to continue development of quantitative retrieval of gas column densities. Fourth, to finish developing the software and hardware required for georeferencing the SEBASS data.

Reusable Launch Vehicle Capability Development

J. P. Penn
Space Launch Operations
G. W. Law
Systems Engineering Division

The objective of the Reusable Launch Vehicle (RLV) Capability Development study is to develop an integrated RLV design and evaluation process. The approach to RLV tool development is modeled after that taken in the development of Aerospace's Concept Design Center (CDC). A team consisting of Aerospace personnel representing various disciplines of RLV concept design and analysis was assembled. Each team member presented a list of model development and model enhancement tasks that would be required to develop the integrated RLV design and evaluation process. The main focus for this year's effort was model development and enhancement in the areas of aerothermal, cost, economics, ground operations, performance, propulsion, and vehicle configuration. Next year's effort will focus on continuing the model development and integrating the models into one RLV design analysis "package."

Corporate Strategic Initiatives

Microelectromechanical Systems (MEMS)

S. Feuerstein, S. Janson, and E. Robinson
Mechanics and Materials Technology Center

Within the DOD and commercial spacecraft industries, reduction in payload weight and concomitant cost savings are important, well-defined goals. Conventional measures such as optimized material selection and improved manufacturing techniques have assisted in this regard, but only to a limited extent. Aerospace staff members foresaw the potential benefits of applying the maturing area of micro/nanotechnology (MNT) to space systems and initiated programs to facilitate its implementation. A microtechnology Corporate Research Initiative (CRI) was begun in FY96 to leverage the advantage of microelectromechanical systems (MEMS), batch processing, and advanced packaging techniques for spacecraft component development. The CRI led to consideration of miniature satellites assembled from MEMS and ASIMS (application-specific integrated microinstruments) and ultimately to the establishment of a Corporate Strategic Initiative (CSI) that specifically addresses exploitation of silicon nanosatellites and microsatellite systems. This first year's effort resulted in the preliminary development of the nanosatellite concept and its application in sparse aperture arrays. Potential opportunities for MEMS component insertion and microsatellite development were also identified.

Center for Orbital and Reentry Debris Studies (CORDS)

W. Ailor
Systems Planning and Engineering Group

The Center for Orbital and Reentry Debris Studies was established in June 1997 as a Corporate Strategic Initiative to focus Aerospace efforts in these important, emerging areas of interest to space users. In this first year of a three-year effort to substantially update and enhance Aerospace tools and capabilities, CORDS was provided with IR&D funds to sponsor related research and tool development. Activities supported ranged from a metallurgical examination of remains of a reentered satellite to development of new tools for analyzing the propagation of debris from on-orbit spacecraft

explosions. CORDS has also purchased a state-of-the-art parallel processing computer that is being used to investigate ways to improve launch and on-orbit conjunction assessment capabilities.

Spacecraft and Launch Vehicles

Spacecraft Battery Performance Simulation System

A. H. Zimmerman, M. V. Quinzio,
L. Wasz, and L. T. Thaller
Electronics Technology Center

The capability to predict the performance of spacecraft battery cells can provide a highly cost-effective tool—both for developing advanced battery designs, and for designing, validating, and operating spacecraft power and thermal subsystems. An integrated Windows-based battery cell modeling system has been developed that allows the performance of nickel-hydrogen, nickel-cadmium, silver-zinc, and all types of lithium-ion battery cells to be accurately predicted. This simulation system is fully validated for the nickel hydrogen, nickel cadmium and silver zinc batteries that are commonly used in spacecraft, and is now routinely used to address performance questions for these batteries. The lithium-ion model has only been validated for one type of commercial lithium-ion cell at present, since this technology has not yet transitioned into space applications. This model has been found to be capable of the accurate performance predictions needed to expedite the emerging development of spacecraft-qualified lithium-ion batteries. Continued refinement and validation will occur as the simulation system is utilized to model performance for other types of lithium-ion battery cells. The use of this simulation system is expected to be critical in helping to develop and optimize lithium-ion battery technology for aerospace applications.

Virtual Motor for Active Combustion Control

J. W. Murdock
Vehicle Systems Division
E. L. Petersen
Technology Operations

Solid rocket motors (SRM) and other combustion devices may experience unsteady pressure fluctuations, resulting in undesirable thrust oscillations and vehicle vibrations. Active control of such disturbances, using timed injection of a small amount of secondary propellant to suppress the oscillations, is a promising alternative to passive damping techniques. This approach eliminates both the thrust oscillations and the corresponding vibrations by reducing the fluctuations at the source level. The results of an extensive literature search indicate that the technology related to the active control of combustion instabilities is relatively immature, and Aerospace is in a position to become a leader in this area. An experimental effort designed to demonstrate an adaptive, active control technique using secondary injection utilizes a subscale cold-flow chamber that models the key features of a SRM. By installing flow disturbances within the model that mimic similar disturbances in a SRM chamber, ordered pressure oscillations at a fixed frequency were demonstrated in the laboratory. An improved test apparatus has been fabricated, and initial work on the secondary injection control scheme has been performed. The simple control scheme will utilize the measured pressure signal as feedback to command the frequency, phase, and amplitude of the secondary injection.

Advanced Aeroelastic Analysis for Flexible Launch Vehicles

S.-H. Chen and K. W. Dotson
Vehicle Systems Division

A numerical procedure for computing the unsteady flows and aeroelastic responses of a flexible flight vehicle with an adaptive dynamic mesh was developed. The equations governing the nonlinear aerodynamics and structural aeroelastic system were simultaneously integrated in time in a fully coupled manner. Steady and unsteady computations were made to validate the accuracy and to demonstrate the applications of the flow solver. Transient flutter analysis of an airfoil was performed to validate the time-marching approach of the aeroelastic calculation. The computational method was used to investigate the aeroelastic response of the payload fairing of an existing launch vehicle in transonic flow.

Nondestructive Evaluation of Composite Materials

J. P. Nokes and R. P. Welle
Mechanics and Materials Technology Center

The focus of this investigation is the development of techniques for detecting and characterizing damage in fiber reinforced composite materials. Fiber-reinforced composite materials are widely used within the aerospace industry. Their high strength-to-weight ratio and

our ability to tailor these materials for specific applications make them attractive for a host of applications. Three tasks were undertaken as part of this investigation: (1) detection of fiber damage in composite materials; (2) development of an indicator coating that, when applied to a composite structure, can indicate the position and intensity of an impact event; and (3) development of micromechanical embedded strain gages for monitoring the effective load capacity of a structure in-vitro. The successful completion of this work has the potential to dramatically impact how composite materials are used in service applications, providing a field inspection capability that is not currently available to the industry.

Advanced Tribological Materials for Spacecraft

G. Radhakrishnan, P. P. Frantz, and S. V. Didziulis
Mechanics and Materials Technology Center

This program aims at optimizing the performance and lubrication of hard coatings deposited on ball-bearing surfaces. High-quality *TiC* films have been successfully deposited at room temperature on 52100 and 440C bearing steels, using pulsed laser deposition (PLD). More recently, the deposition has been extended to a high-fatigue-strength REX20 steel substrate. A variety of analytical techniques have yielded important macroscopic and microscopic film properties. In-situ spectroscopic measurements are being used to identify atomic and molecular species generated by laser ablation. These data, in conjunction with macroscopic film properties, will be used to optimize deposition parameters. To develop optimized lubrication schemes for hard coatings, spectroscopic and scanning probe techniques were applied to model studies of the interactions of single crystal surfaces with simple adsorbate molecules. The studies on single-crystal *TiC* are currently being extended to thin films of *TiC* deposited in this program. Atomic force and friction force microscopic studies are being conducted on surfaces of the same materials in a collaboration with the University of Houston. These three efforts are jointly contributing toward an increased understanding of the surface microstructure and tribological performance of hard coatings.

Advanced SEU Test Facility

R. Koga
Space and Environment Technology Center

The objective of this program is to improve the single event upset (SEU) test facility at the Lawrence Berkeley Laboratory (LBL) 88-inch cyclotron and to make certain that the ions at the test facility have proper characteristics to measure the SEU sensitivity of microcircuits. Relativistic heavy ions have been compared to ions of comparable linear energy transfer (LET) values available at the Lawrence Berkeley Laboratory 88-inch cyclotron regarding their influence on SEU sensitivity in selected microcircuits. Even for very high energy ions, LET remains a useful parameter for plotting SEU sensitivity.

Advanced Spacecraft Propulsion

M. W. Crofton, J. E. Pollard, B. B. Brady, T. Moore, E. J. Beiting, and R. B. Cohen
Mechanics and Materials Technology Center

In the past year, a laboratory ion engine was constructed according to a novel design, the effect of natural radiation on spacecraft during orbit transfer was analyzed for the case where advanced propulsion devices are utilized, and the orbital parameters for several scenarios were determined. New diagnostic techniques have been developed and applied, and major contributions to a new book have been provided. The project has been an outstanding catalyst for developments in micro-propulsion and nanosatellite technology, has produced a revolution in the techniques of electric thruster evaluation, and has been effective in advancing the development and implementation of electric thruster technology by the Air Force and prime contractors.

Vibroacoustic Modeling Benchmark Study

C. S. Tanner and T. T. Do
Vehicle Systems Division

The objective of this program is to evaluate commercial vibroacoustic software for its usefulness in solving typical spacecraft and launch vehicle problems, and to develop a modeling capability and expertise for application on DOD and commercial programs. The two-year effort evaluated commercially available software and purchased two packages; completed the modeling of the vibration response of a fairing surface and the internal acoustic level; and provided training in the use of the tools. In addition, a model of the Titan IV on the launch pad was partially completed, while the extraction of stresses for the antenna problem is awaiting a software upgrade to Sysnoise. We have gained insights in the use of these tools by comparing model output with test and/or flight data and provided feedback to the technical community through presentations at seminars and workshops.

Vibroacoustic Intelligent System For Predicting Environments' Reliability and Specifications (VISPERS)

D. Wong
Space Launch Operations

Prediction of vibroacoustic environments for both DOD and commercial launch vehicles, as well as spacecraft, has become a costly, labor-intensive process. Yet such analysis is essential to ensure the reliability of vehicle structures and airborne equipment. The objective of this R&D program is to develop a software package that uses a combination of theoretical and empirical methods in an automated sequence to provide predictions of vibroacoustic and shock environments. This intelligent design tool will enable more responsive, cost-effective, and accurate analyses than are currently possible. The software to be developed will incorporate a graphical user interface and multiple modular analysis tools. The program will utilize standard input/output data formats, so that the results from other analytical prediction tools may be imported for further processing. The user will also be able to generate predictions based on data drawn from a dedicated database. The development plan for this design consists of three phases: Phase I—Top Level Requirements Specification and a Development Roadmap; Phase II—Generation of Software Prototype; Phase III—Full Scale Program Development. This report documents the work completed under Phase I.

Fracture Testing of Nonlinear Viscoelastic Material

S. T. Chiu
Vehicle Systems Division
D. J. Chang
Technology Operations
K. W. Gilbert
Air Force Space and Missile Center

The objective of the project is to develop a standard test procedure for determining the fracture toughness of solid rocket propellant. The fracture toughness can then be used to characterize the criticality of defects and contamination in a solid rocket motor. In FY98 we completed the fabrication of a pressurized chamber for testing propellant material under realistic rocket motor operating conditions. Fracture testing of an inert material was conducted using dog bone specimens. Based upon a review of new and existing data, a rectangular 3-inch by 1-inch specimen was selected for use in future testing. Hyperelastic finite-element analyses of a rectangular specimen showed good correlation with empirical J-integral value. Additional finite-element analyses were performed demonstrating the benefit of 3-dimensional analysis by modeling a surface flaw in a motor center segment and quantifying the effects of a crack length-to-depth aspect ratio. The test data generated will assist the solid propellant community in selecting a standard fracture test specimen. The hyperelastic and 3-dimensional finite-element analyses demonstrate Aerospace's state-of-the-art analytical capability.

Advanced Ignition and Combustion Concepts for Launch Vehicles

B. B. Brady, E. J. Beiting, and T. Moore
Mechanics and Materials Technology Center
J. C. Wang
Vehicle Systems Division

In the third and final year of this project we have made progress in building an experimental capability and constructing a model to study cryogenic droplet ignition. We are seeking additional support from both commercial companies and Air Force program offices. An increased understanding of droplet ignition is essential to reliable launch vehicle operations, liquid-fueled upper stage restart, and range safety in handling of cryogenic fuels.

Space Launch Operations Telemetry Acquisition and Reporting System (STARS)

M. S. Sazani
Space Launch Operations / Western Range

The Space Launch Operations (SLO) Telemetry Acquisition and Reporting System (STARS) was conceived to provide Aerospace launch site personnel with the capability to independently analyze launch vehicle test data. The El Segundo STARS was designed to provide remote support of launch vehicle processing and countdown/countup activities at Cape Canaveral and Vandenberg Air Force Base (VAFB). The activities of the sixth year of the STARS project have provided Aerospace personnel with the capability to independently process Titan IVA, Titan IVB, Titan II, Titan/Centaur, Delta, and Atlas/Centaur vehicle telemetry data. An expert system interface was implemented, providing automated event processing. Vehicle-specific knowledge bases were developed and utilized during Titan II and Titan IVA missions. Data Reduction Center software is fully integrated in the Western Range (WR) STARS facility, providing remote database development prior

to use at the site. WR STARS generates test data files in Corporate Telemetry Database (CTD) format, providing a common Corporate analysis capability for both site-resident test data and El Segundo-resident flight data. STARS is used on a regular basis in the WR vehicle operations and El Segundo remote launch support activities.

Space System Contamination Modeling

B. W. Grange
Planning and Communications Division

G. S. Arnold, D. J. Coleman, and D. F. Hall
Mechanics and Materials Technology Center

M. A. Marvasti, P. A. Nystrom, and T. R. Simpson
Computer Engineering Subdivision

W. D. Fischer
Vehicle Performance Subdivision

Operational experience and dedicated experiments have shown that space systems are degraded by contamination from outgassing, transport, and deposition onto surfaces. Optical, solar power, and thermal control subsystems are usually the most contamination-sensitive. The durability of a space system to contamination effects is usually demonstrated by modeling or similarity. Aerospace currently possesses little or no capability for independent assessments of contamination analyses that rely on large-scale contamination modeling. The goal of this two-year program is to produce a 3-D, multi-nodal contamination transport, deposition, and effects model for independent evaluations of space system designs and operations and in resolving satellite anomalies. The computer model will build on the Corporation's substantial investment in satellite thermal modeling. We are applying the latest understanding of long-term contamination phenomena developed at Aerospace and elsewhere, and we are employing the latest test databases being developed by the US space industry. Significant progress has been made in the areas of model architecture, definition of physical phenomena, controlling equations and their parameters, and a substantial amount of code has been written and tested.

Adhesive Bonding of Polymer and Composite Surfaces

R. A. Lipeles and T. W. Giants
Mechanics and Materials Technology Center

The objective of this program was to develop an advanced technique to characterize adhesive surfaces. Better characterization of adhesives will lead to improved handling procedures for elastomer and resin adhesives and improved fabrication of bond joints, which will result in higher yield, more predictable bond integrity, lower cost, and greater strength in structural assemblies. Using atomic force microscopy, we demonstrated the effect of toluene exposure on silicone adhesive, resulting in swelling. The surface of the adhesive showed definite topographic features related to the exposure. Furthermore, force versus displacement measurements of attractive and adhesive force between the probe tip and toluene exposed- and dried-silicone surfaces showed much higher forces for toluene than water. Water is known to interact only weakly with the silicone surface. However, toluene swells the surface and probably changes the configuration of the silicone polymer chains on the surface, resulting in increased adhesion forces. This technique can detect exposure and possible damage to silicone adhesives even after the solvent has dried. We believe that this technique can be used to characterize adhesives and can lead to effective resolution of adhesive anomalies due to inadvertent exposure to damaging solvents.

Automated Progressive Damage Analysis for Composite Structures

C. C. Lee
Vehicle Systems Division

A progressive damage structural analysis code is being developed for the evaluation of three-dimensional composite structures. This code, when fully developed, will track propagation of local damage in structures at any stage of loading and show the state of stress and strain for the whole structure. The public domain NIKE3D code was selected to implement the progressive damage analysis approach. A major portion of the required subroutines has been written. Once the program is complete, it will become a valuable tool for structural evaluations, design verification, and anomaly investigation of many advanced composite structures used in DOD and non-DOD space systems.

Electronic Device Technology

Short Pulse X-Ray Generation for Single Event Effect Testing of Electronics

S. Moss and S. Humphrey
Electronic Technology Center

The objective of this program is to develop a short-pulsed x-ray facility for single event upset testing of microelectronic devices. The development of a short-pulsed x-ray facility will enhance our radiation effects testing capabilities by making it possible to probe devices whose sensitive nodes are covered by metalization using laser-generated pulsed x-ray techniques, instead of more expensive and device-damaging high-energy particle facilities.

Photonics for Space Systems

T. S. Rose and D. Gunn
Electronics Technology Center

The goal of this program is to investigate photonic components and concepts important to space-based optical communication systems. Our efforts this year focused on radiation effects in *Er*-doped fiber amplifiers (EDFAs), which are key elements in high power transmitters and low noise receiver amplifiers for optical communications at 1550 nm. Comparative gamma and proton irradiation tests were performed on several commercially-available fibers to investigate their sensitivity to both types of radiation. In addition to radiation testing, we also began efforts to develop fiberoptic Bragg gratings (FBGs) for filtering and signal modulation. These components have numerous applications in signal processing, distribution, and timing.

Multiplexed Fiberoptic Sensor Systems

C. M. Klimcak and B. Jaduszliwer
Electronics Technology Center

We have investigated fiberoptic Bragg grating sensor demultiplexing schemes and built laboratory testbed demonstrations that highlight the utility of employing multiplexed fiberoptic sensors in spacecraft applications. These testbeds have been used to demonstrate temperature and vibration detection, cure monitoring of composite materials, rotor bearing vibration sensing, and the detection of impact location and magnitude with a distributed sensor array. Although this IR&D program is now being brought to a close, we expect to continue impact sensing work as we build a prototype full-scale impact monitoring and assessment system for graphite composite solid rocket motors.

Infrared Optical Parametric Oscillators

D. Chen and R. A. Fields
Electronics Technology/Center
J. D. Barrie
Mechanics and Materials Technology/Center

Efficient, compact and tunable solid-state IR laser sources are needed for many space and environmental applications. Continuous wave (cw) tunable light sources near 3 μm and 4–5 μm are needed for calibration of optical sensors on several government satellite systems. In addition, pulsed eyesafe sources are needed for studying phenomenology of the atmosphere. During the first and second years of this IR&D project, we have successfully generated 450 mW of useful single-frequency output power near 3 μm using a newly-developed nonlinear material known as "periodically poled lithium niobate" (PPLN) as the nonlinear crystal in an optical parametric oscillator (OPO). We also successfully scaled the technology up to 5 W output with a conventional (non-pump-resonant) OPO confuguration. These devices demonstrated tunability compatible with atmospheric transmission constraints. For the 1.5 μm eyesafe pulsed laser, we demonstrated up to 7 W output power at a 100 Hz pulse rate. In this final year, we have successfully demonstrated up to 70 mW usable coherent output at 4.3 μm using a dual-grating PPLN crystal. The dual-grating PPLN was used to combine OPO and difference frequency generation (DFG) of two nonlinear processes in a single PPLN crystal. The major advantage of this technique is the threshold reduction for generating 4–5 μm radiation. The successful demonstration of this all-solid-state 4–5 μm tunable laser source should provide a second color for the MWIR sensor calibration.

Non-volatile Memories for Space Systems

D. M. Speckman and M.S. Leung
Electronics Technology Center

Ongoing improvements in the ability to store and manipulate satellite data are necessary in order to

enhance mission capabilities and ensure on-board autonomous operation and on-orbit data processing. To this end, we have been involved in the development of advanced recording and data storage technologies, specifically concentrating our activities on the development of high capacity, non-volatile memories such as magnetoresistive random access memories (MRAMs). As part of this effort, we have been developing novel methodologies for the synthesis of colossal magnetoresistive (CMR) thin films with low cost and high throughput for potential future MRAM applications. During this fiscal year, we have deposited thin films of CMR materials onto a variety of substrates likely to be employed in commercial devices using a simple, sol-gel technique, and have studied the properties of these films. We have also carried out experiments designed to understand and ultimately enhance the magnetoresistive effect of these CMR materials. The successful development of these materials will ultimately allow for a dramatic increase in the memory density of MRAM devices.

Application-Oriented Microwave Amplifier Reliability Test Advancements

K. J. Russell, R. J. Ferro, and L. O. Duffy
Electronic Systems Division

A facility to perform temperature-accelerated aging of up to 30 microwave transistors in normal operation was made operational and applied to power microwave field effect transistors. The transistors used are representative of those found in Air Force systems. Temperature-accelerated aging under different operating conditions, together with pre- and post-aging electrical characterization and analyses, are used to determine what conditions are necessary to predict life and mechanisms of failure. The purpose of obtaining this information is to (1) increase the ability to predict the life of solid state amplifiers, (2) decrease the cost of life prediction, and (3) provide screening techniques to prevent defective, or unsuitable, transistors from being used. Pre-aging characterization of the transistors has been performed and aging tests are underway. Degradation limits have been reached for two groups of transistors, and analysis of anomalous transistor behavior is being examined. Tests of the hot carrier effect have been initiated.

VLSI Design and Rapid Prototyping

R. T. Bow, G. Gerace, and H. Hou
Electronic Systems Division

A computer-aided design process for digital communication system design and prototyping has been integrated and tested. By combining and integrating third-party CAD tools with Aerospace's internally developed Very Large-scale Integrated Circuit (VLSI) modeling, verification, and implementation tools, this IR&D effort has provided The Aerospace Corporation with the capability to rapidly develop hardware prototypes of advanced systems that can be re-implemented into an Application Specific Integrated Circuit (ASIC) chip. This capability is being developed through a cooperative effort utilizing expertise across three subdivisions within the Electronic Systems Division. As a result of having developed a highly-efficient VLSI design and rapid prototyping capability, this project is also providing rapid prototypes for validation of key Aerospace-patented technologies. These include modulated lapped transform image compression, Gaussian Minimum Shift Keying (GMSK) waveform studies, Global Positioning System (GPS) studies, and turbo encoding and decoding.

Communications and Navigation Technology

Deterministic Noise Techniques for Secure Communications

C. P. Silva and A. M. Young
Electronic Systems Division

This IR&D project has succeeded in developing wideband, high-frequency communications system prototypes using chaotic carriers, synchronization, and modulation that would be suitable for both satellite and ground-based applications. Because of the unique properties of chaos, such a system can provide several potential benefits, including inherent security features provided by the carrier, novel spread-spectrum and frequency-reuse capabilities for wideband communications, enhanced synchronization characteristics, and other unique signal processing operations. The long-standing challenge of the implementation of wideband, high-frequency chaotic oscillators was overcome this year with the fabrication and demonstration of several prototypes with increasingly higher operating frequencies. This achievement validated the new oscillator design methodology invented late last year. The highest frequency oscillator had a significant bandwidth of around 125 MHz and was forced at about 100 MHz, exhibiting a remarkable preservation of the baseband phase portrait despite circuit delays corresponding to over 90° of phase shift, and allowing for the adjustment of the spectral shape of the chaos (a very desirable

signal design feature). A microwave version of the oscillator was also designed, simulated, and laid out for fabrication, and preliminary work on the synchronization of such oscillators was also completed.

QSSB/QVSB Digital Data Transmission

J. Poklemba and G. Mitchell
Northern Virginia Office—Engineering Technology Group

The objective of this project is to develop bandwidth-efficient digital data transmission schemes whose performance approaches the Shannon channel-capacity bound by employing quadrature single-sideband (QSSB) and quadrature vestigial-sideband (QVSB) techniques. These methods allow higher-rate data to be transmitted through a given allocated bandwidth—when compared to conventional methods—by maximizing the number of bits/s per Hertz.

One of the main thrusts of this effort is to find signaling waveshapes of minimum bandwidth that exhibit relatively little crosstalk with quadrature carrier SSB/VSB transmission, thereby requiring only a modest increase in signal-to-noise ratio (SNR) over conventional double-sideband transmission. Additionally, modulator and demodulator/maximum-likelihood-sequence-estimator (MLSE) structures need to be developed. The MLSE developed during this effort should be able to unravel the desired signal from known or estimated crosstalk using the well-known dynamic programming optimization algorithm developed by Viterbi.

Tomography of Electron Density in the Ionosphere (TEDI)

J. R. Jameson
Electronic Systems Division

The major goal of this project is to use GPS data to obtain useful three-dimensional electron density profiles of the ionosphere. Such profiles enable the prediction of radio propagation delay through the ionosphere, improve our understanding of space weather, and can improve the accuracy of space-based sensors. The approach used is to represent the ionospheric electron density as a weighted sum of known representative density profiles, and to adjust the weights by incorporating GPS measurements through an optimal statistical procedure called Kalman filtering. This year, Aerospace developed procedures to obtain hourly GPS data from over 138 sites worldwide and obtained software to perform data reduction, orbital ephemeris prediction, and parametric ionospheric modeling. In addition, a preliminary version of the Kalman filter was written. In the next year this project will continue (under a different title) to further develop the filter and models.

Information Science

High Performance Computer Communication Networks

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Computer networks are becoming a critical and pervasive national infrastructure for military and commercial applications. The Internet, which is the interconnection of a variety of networks, operates as a single worldwide system for information exchange. To enable network-based applications, there is a growing recognition that more capable computer-communication networks are necessary to implement advanced computer systems for unique military space requirements. Increasingly, military and commercial satellites are being used as essential components of heterogeneous computer networks for space systems. Our objectives are to evaluate, develop, and demonstrate communication protocols needed for high-speed, low-latency, reliable and secure data transfer; and to develop network-management software to manage large, heterogeneous, high-speed networks, including intrusion detection.

To support Internet services in a Global Broadcast service (GBS) network, we developed and demonstrated enhanced, compatible versions of standard Internet protocols including multicast for asymmetric connections. Our enhanced compatible protocol for asymmetric broadcast networks (VIPRe) has been submitted as an Internet Draft. We continued testing and evaluating emerging technologies such as: multi-hop wireless networks, collaborative visualization tools, the InCharge event correlation system from System Management Arts, and traffic monitoring tools for network management and intrusion detection.

Satellite Link and Mobile Mesh Multicast (SLAMMM)

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Wireless mobile computing and communications environments are now major components of information

superiority. However, even though advances have been made in the related computing and communications technologies, the infrastructure required to integrate these technologies and use them in a battlefield situation needs further development. This is particularly true in the areas of routing and reliable multicast protocols.

The research goals of this project are as follows: (1) to investigate issues and find solutions for the efficient and reliable operation of multicast routing protocols in heterogeneous network environments (including channel access protocols for multicasting in mobile mesh networks), (2) to analyze and simulate these protocols, and (3) to demonstrate their use with Internet-based applications in an experimental testbed environment that includes satellite links and mobile nodes.

This is a collaborative research project between The Aerospace and MITRE Corporations. The research is organized into three teams, each staffed by members of both corporations. The first team is conducting protocol analysis and design, and is jointly led. The second team is developing a demonstration and experimentation environment, and is led by The Aerospace Corporation. The third team is developing a discrete event simulation environment and relevant simulation models, and is led by The MITRE Corporation.

Information System Technologies

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Systems Engineering Division

Information is now viewed as the key to the continued dominance of our military forces. The objective of this project is to explore and develop innovative technologies for the development of future information systems. The emerging model for these systems is a push-pull information architecture based on the World Wide Web. During FY98, we studied a number of upcoming technologies. Intelligent agents will assist people with daily tasks and interact with both users and other agents. XML, a standard for text markup languages and meta-data, will allow structured data to be shared and viewed over the Web. Online collaboration tools offer new features that enhance the productivity of geographically-separated teams and allow for courses and presentations to be provided online. Java is proving its usefulness for platform-independent development through improvements in performance and its feature set. Also, as the Web is maturing, evaluating innovative commercial products is becoming increasingly important. We installed and tested a number of promising products, including the 10 servers contained in the Netscape Suitespot package, Microsoft NetMeeting, ICQ (a collaborative internet locator), and IBM ViaVoice. Knowledge gained from this research is being used to advise our customers and to enhance our corporate Intranet.

Joint Technical Architecture (JTA) Evaluation and Experimentation

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M. Marvasti, K. Nakashima, M. Noyes, and M. O'Brien
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In support of information superiority, the DOD has mandated that the Joint Technical Architecture (JTA) information system standards be used in all new and upgraded C4I systems and interfacing systems. The goal of JTA is to promote software portability and interoperability between DOD systems. The JTA mandates the use of the Defense Information Infrastructure Common Operating Environment (DII COE), a collection of information system products that include government-developed and commercial software, along with rules for putting them together. A number of SMC and NRO program offices have asked for Aerospace technical advice and assistance in their consideration of migrating to JTA compliance. The purpose of this project is to broaden Aerospace's technical understanding of the issues affecting portability and interoperability between information systems, to develop expertise in the use of JTA standards and COE products, and to influence their future direction. We analyzed the standards currently in the JTA, investigated emerging information system standards, established a testbed for assessing compliance with current COE architectures, and investigated the incorporation of new security products into COE.

Software Acquisition Process Definition and Improvement

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The primary objective of this research has been to define new and/or improved processes to be used by The Aerospace Corporation to support the national security community in the acquisition of large software-intensive systems, such that these processes will satisfy the Software Engineering Institute's (SEI's) Software Acquisition Capability Maturity Model (SA-CMM) and will comply with the acquisition portion of the international standard on software life cycle processes, ISO 12207. During the first two years of research, a model of the Aerospace software acquisition processes, called the Aerospace Software Acquisition Process Model, was developed that satisfied these requirements. During this third and last year of research, use case modeling

techniques were utilized to demonstrate how to apply and tailor the Aerospace software acquisition processes defined by the Aerospace Software Acquisition Process Model to support a specific program. The results of this research include recommendations for improved software acquisition processes for supporting Aerospace's primary customers. In addition, the software acquisition processes defined by this research can provide a basis for the definition and improvement of software acquisition processes to be used by SMC, the NRO, and other organizations in the acquisition of large software-intensive systems.

Framework-based Software Architectures for Satellite Ground Systems

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Building one-time solutions for satellite ground systems (SGS) results in systems that are difficult and expensive to maintain. Developing ground systems that reuse a successful architecture design is a viable approach to reducing cost. The objective of this effort is to develop object-oriented architectures for the major components of a satellite ground system using a frameworks-based approach. Frameworks are useful for defining a general architecture once and applying that architecture repeatedly, customizing it as necessary to meet the specific requirements at hand. Four primary tasks were performed during the year: (1) definition and documentation of framework architectures for common ground system components including telemetry analysis, satellite commanding, orbit management, and attitude management; (2) implementation of an application framework for telemetry analysis; (3) investigation of product lines, architecture evaluation criteria, and COTS modeling approaches; and (4) participation in activities that foster community consensus on important architectural issues for SGS.

Information Technology Systems Security

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J. Betser, P. Stelling, and S. Wang
Computer Systems Division

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Corporate Information Resources Division

The increasing complexity, diversity, and interconnectivity of computer systems has created a growing concern for the vulnerability of all connected systems. The greater ease of access to global data communications and control systems is one of the most prominent factors contributing to the expanding population of sophisticated computer intruders. In an effort to keep up with increased vulnerabilities and more advanced intrusion techniques, product developers and network security administrators are caught in a never-ending race to head off intruders. Unfortunately, the rush to market products, followed by add-on security functionality, often results in poorly implemented and inadequate security controls.

Through our work with many organizations, we have identified a growing need to find longer-term security solutions that are effective, usable, and interoperable. To address this need, we created the Trusted Systems Laboratory (TSL) where we test security products running on multiple platforms with multiple interconnected applications.

Environmental Technology

Upper Atmospheric Structure Effects

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This project provides models and measurements of upper atmospheric structures needed for implementation of future sensor systems. These include (1) the characterization of small-scale structures in the 80–100 km altitude region due to atmospheric gravity waves (AGWs); (2) a model for persistent missile wake emission in the 80–300 km region; and (3) an improved description of compositional and density changes in the 100–300 km region due to auroral energy input. During the first year of this project substantial progress has been made in the interpretation of a variety of upper atmospheric phenomena. Specifically, during this first year we have shown that small-scale AGWs can propagate thousands of kilometers away from their source, and the Aerospace Plume/Atmosphere Chemiluminescent Clutter Model (PACCM) has been upgraded with a detailed, temperature-dependent chemical mechanism for the combustion of hydrocarbon fuels with oxygen atoms based on laboratory measurements.

Mesoscale Prediction and Toxic Dispersion

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Space and Environment Technology Center
D. G. Brinkman
Advanced Technology Division
I. A. Min
Systems Architecture and Plans Subdivision

This project is a response to requirements across a broad range of programs for an Aerospace capability in atmospheric prediction pertaining to atmospheric effects on space systems. Specific areas of concern are toxic dispersal related to launches, tests and spills; point specifications of meteorological parameters; radiative backgrounds (clutter); and ephemerides, re-entry and collision avoidance for space systems. We have (1) simulated wind flow over the ranges, (2) applied a model of upper atmospheric dynamics to the response of the Jovian atmosphere to the Shoemaker-Levy 9 cometary impacts and reconciled discrepancies between earlier work and Hubble observations that had far-reaching implications for theories of the formation of the Jovian atmosphere, (3) analyzed airglow images and performed model simulations and found that thermally-ducted atmospheric gravity waves (AGWs) are present and that winds can detune these waves, thereby affecting wave directionality, (4) simulated the propagation of AGWs through wave backgrounds and found that the observed high-wavenumber tail of the wave spectrum can be explained by the time-dependency of the background wave field, and (5) extended our theoretical work on wave-driven airglow emissions to include the atomic oxygen transition radiating at 5577Å and spectrally analyzed data from Arecibo Observatory, Puerto Rico and found wave-driven fluctuations that suggest strong wave reflection.

Space Weather Modeling and Analysis

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An averaged worst-case energetic electron flux spectrum at geosynchronous (GEO) orbit was constructed from National Oceanic and Atmospheric Administration Space Environment Center (NOAA-SEC), Los Alamos National Laboratory (LANL) geosynchronous and CRRES data. For the high-earth orbit (HEO) an average worst case spectrum was generated from LANL-GPS, HEO, and CRRES data. These worst-case spectra were provided as preliminary GEO and HEO deep dielectric charging specifications for military satellite programs.

A database of DMSP low-altitude data during solar maximum and minimum was created. In an initial search we have found that high-level charging events occur more frequently than previous studies have indicated for solar minimum. This is because the thermal plasma density, which tends to prevent surface charging, was extremely low during the last solar minimum period.

Preliminary testing of our improved Magnetospheric Specification Model (MSM) was completed. The order of magnitude and radial variation of quiescent plasma sheet pressure profiles obtained from our model agreed with published observations from the ISEE, AMPTE, and DMSP satellites. During disturbed times there is an enhanced pressure gradient extending from 6 to 15 earth radii along the midnight meridian, which is in qualitative agreement with observations.

Surveillance Technology

Dual Use of Surveillance Satellites: Data Fusion and Analysis

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Space and Environment Technology Center
B. J. Tressel and C. J. Lee-Wagner
System Development and Operations Subdivision

Fires of various types and volcanic eruptions are examples of natural events that need to be better monitored for disaster mitigation, forest management, and environmental monitoring purposes. Defense Support Program (DSP) satellites possess currently under-exploited capabilities to detect and characterize certain types of natural phenomena. The Aerospace Corporation, in collaboration with federal agency, university, and industry coworkers, is participating in experiments that evaluate the ability of several different space systems, including DSP, to perform disaster detection and environmental monitoring missions. Prototype satellite ground station hardware and associated software are being refined and used to perform operational tests. The results from this research are being used to help guide development of a disaster detection and mitigation program run by the United States Geological Survey called the Hazard Support System.

Civil, Commercial, and International Remote Sensing: Technology & Applications

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The objective of this program is to survey, categorize, and critically compare the characteristics of burgeoning civil, commercial and international (CCI) space-based remote sensing systems, sensors and products. The field is on the cusp of tremendous change with the advent of international proliferation, commercialization, small satellites, high-resolution systems with sub-meter resolution, and hyperspectral systems. This year, systems of 23 countries from 1980–2007 were examined. A pilot relational database of these systems—which will become generally available in FY99—was completed, and the ability to rake a set of user benchmarks across that database to identify all systems of potential interest was demonstrated. In terms of products, a study of future trends in geospatial data processing and geographical information systems (GIS) was completed. A pilot data set of co-registered imagery from a representative cross-section of systems was built, combined with ground and infrastructure data using GIS techniques, and an initial assessment of its military utility performed. Owing to the failure of three commercial systems during this period, and the postponement of others, the collection and assessment of imagery from high-resolution, digital commercial systems was not performed. These are two of several major goals for next year.

Issues in Remote Sensing

D. K. Lynch, J. H. Hecht, and B. R. Johnson
Space and Environment Technology Center

During this last year of this project we made considerable progress in understanding noctilucent clouds (NLCs). NLCs are the highest clouds in the Earth's atmosphere, occurring typically between 80 and 85 km at latitudes above 55 (or below –55) degrees during the polar summer. They are a potential source of clutter in some remote sensing systems. This year we concentrated on two fundamentals of NLCs: the size and composition of their constituent particles. We used our ultraviolet spectrophotometer to measure the brightness and polarization of noctilucent clouds from a site in Greenland. We were able to determine the average size of the particles, a primary goal of this project, as well as clear evidence of NLC particle size distribution. We have also modeled the spectra, and preliminary results show that we may have been the first to positively identify water ice as the primary constituent in NLCs. We also made two computational advances in understanding the heterogeneous character of NLC particles. The first is the development of a new effective medium theory for estimating the dielectric function of ice. The second was the development of a new, computationally-simple means of computing scattering coefficients of nonspherical particles.

Infrared Spectral/Spatial Instrumentation and Measurements

R. W. Russell, D. K. Lynch, G. S. Rossano, and R. J. Rudy
Space and Environment Technology Center

This project utilizes a variety of infrared instrumentation designed and developed in-house to make IR measurements of target signatures and backgrounds to support architecture studies, signature evaluation, on-orbit calibration of IR sensors, and astronomical and aeronomical research. Instrumentation includes imagers, spectrographs, and imaging spectrographs, which together span the spectral range from the near IR through the longwave IR (~0.8 to 15 μm). We are currently developing new state-of-the-art generic array electronics that will be applied to at least four of our 2D array-based IR sensors; we expect the system to be operational in the first half of FY99.

In the past year our Near IR Imaging Spectrograph (NIRIS) was used to observe sources from the 2MASS Survey (an all-sky survey at 1.25, 1.65, and 2.2 μm), several small moons of the outer planets, asteroids, active galaxies and quasars, and novae and supernovae. In the thermal IR (3–14 μm), work has begun on an LWIR imager using an array from the SBIRS program, and the Broadband Array Spectrograph System (BASS) has turned its enhanced accuracy and sensitivity to laboratory flame studies, the space threat of meteoroids, and the development of a capability to provide timely reference stellar spectra for variable stars that can be used for on-orbit IR sensor calibrations.

Remote Sensing Architecting Strategies

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Traditional and non-traditional Aerospace customers are facing new challenges as the government looks for ways to reduce cost and promote interoperability across

multiple systems. Many new customers have limited budgets and system needs which require unique system solutions. For example, the Defense Intelligence Agency's Central Measurement and Signature INTelligence (MASINT) Organization (CMO) needs a system that will enable them to provide centralized management across multiple MASINT assets neither owned nor operated by the CMO. These challenges require new architecting strategies to clearly define and communicate system options before decisions are made on what needs to be built, if anything. Five alternative architecting strategies were developed and applied to sample customer problems. They include a functional system strategy, a management system strategy, a data exchange system strategy, a technology-based system strategy, and the more traditional physical system strategy. One or more of these strategies could be used by architects to help define and solve the system needs of emerging customers with unique problems and technology interests.

AHI SEAL East Coast Installation

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J. A. Hackwell
Technology Operations

The objective of this program is to extend to the East coast the capability for data reduction and analysis of infrared hyperspectral remotely-sensed data taken with the Spatially Enhanced Broadband Array Spectrograph System (SEBASS) sensor. This goal was realized in the creation of the Spectral Applications Laboratory on the East coast, which has a computer system dedicated to the processing of SEBASS data using the Spectral Exploration using Automated Logic (SEAL) software system.

Systems Engineering

Costs of Space, Launch, and Ground Systems

S. A. Book, L. B. Sidor, H. S. Shim, and M. S. Alvarez
System Development and Operations Subdivision

Government military and civilian agencies involved in the space-system acquisition decision-making process today consider cost to be a significant performance criterion. Indeed, under the "cost as an independent variable" philosophy, anticipated cost growth may today lead to reductions in performance and capability (and, in extreme cases, to program cancellation), rather than to routine acceptance of cost overruns as in the past. It is therefore vital that all personnel representing The Aerospace Corporation understand costs of historical and current space systems and at least the essentials of costing jargon, practices, procedures, and issues. The FY98 phase of this ongoing effort is intended to contribute to significant progress in enhancing corporate understanding in these areas. Preparing for a Summer 1999 release of the 8th edition of the updated and expanded corporate briefing on cost entitled "Costs of Space, Launch, Ground Systems," this year's data-gathering effort resulted in new cost information on the International Space Station; launch facilities, pads, and supporting structures at Vandenberg and Cape Canaveral; and (in cooperation with The MITRE Corporation) ground control and communication systems.

Systems Engineering Tools for Mission Performance and Utility Analysis

R. W. Reid, Jr., J. Yoh, T. J. Lang, H.-K. Lee, M. J. Barrera, T. J. Mosher, N. Y. Lao, C. C. Reed, and D. J. Goldstein
Systems Engineering Division

D. Y. Buitrago and R. H. Weber
Strategic Awareness and Planning Directorate

The Functional Requirements Analysis of Mission Effectiveness (FRAME) methodology and analysis tools and team have been created to support concept development efforts that include military space systems in the force architecture. The FRAME methodology is a step-by-step procedure for defining the user problem, laying out alternative solutions, setting solution requirements, and creating a conceptual design which meets the requirements

The FRAME team has transitioned to the Concept Design Center's (CDC) System Architecture team, as this effort and the CDC IR&D effort have merged resources and capabilities. This CDC System Architecture structure features satellite payload, constellation coverage, constellation availability, satellite design, launch vehicle support, communication/ground segment, and satellite system life-cycle cost models.

Warfare modeling research addresses two of the major challenges in modeling combat outcomes to space system performance: (1) capturing sufficient cause-and-effect fidelity, and (2) making the cause-and-effect linkage between inputs and outputs understandable and believable. The present work is aimed at developing a quick-reaction, rapid prototyping experimental testbed for warfare modeling that will allow

modelers to test and experiment with methods of modeling fundamental cause-and-effect mechanisms, and will drive the necessary cause-and-effect insights needed for campaign simulation upgrades.

Concept Design Center

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The Concept Design Center (CDC) is being developed to maintain The Aerospace Corporation's position as a world leader in conceptual space system design and analysis. The CDC provides an interactive, realtime conceptual design environment that allows the Corporation's customers to work more closely with engineering experts from the Engineering and Technology Group (ETG). Conceptual design, technology insertion, and trade space exploration studies that required months to complete can now be addressed in a matter of weeks. The CDC makes efficient use of resources while producing higher quality results.

The CDC processes are changing the way ETG members relate to each other, the program offices, and our customers. Customers and study coordinators are able to interact with the team during the design process to provide feedback on the mission and goals of the study to ensure that the final product meets their needs. By encouraging involvement by all interested parties and formalizing the exchange of information, it has been possible to enhance the detail and consistency of our products while improving team productivity and effectiveness.

Advanced Technologies for Space Systems

M. J. Barrera and J. M. Lyons
Systems Engineering Division

The objective of this project is to evaluate the impact of various advanced technologies on the design of modern spacecraft. This year, information was gathered from commercial and government agencies to assess the current state of the art in space hardware as well as near-term and future trends in the industry. This research provides the necessary background information for the evaluation of space system concepts incorporating new technologies in their design and serves as a starting point for a more detailed inquiry to space hardware technology readiness.

We have observed that many of the significant advancements in space hardware have been prompted by advances in the commercial sector. In particular, the development of lightweight, efficient electronics has enabled improvements in the areas of data processing and storage, power systems, communications, and attitude sensing. These improvements will enable higher performance spacecraft with lower weights and costs.

Space Planning & Architecture Decision Environment (SPADE)

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R. Crawford
Computer Systems Subdivision

This work exploits previously developed software technology for rapid application development in Smalltalk to explore how both that language and Java code can be used in conjunction for graphic editing of complex input files for object-oriented combat simulations. As operation and distribution of combat simulation code moves from dedicated platforms to an Internet environment, features of the rapidly evolving Java language are advertised as advantageous. This work compared the relative strengths of Smalltalk and Java as applied to a specific application of great importance to combat simulation and military utility analysis of space systems.

Risk Quantification for New Spacecraft Concepts and Technologies

S. B. Guarro
Electronic Systems Division

The objective of this IR&D project is to develop and demonstrate a methodology and its related software tools to perform quantitative technical risk evaluations of new space system and spacecraft concepts and technologies. With the aid of a quantitative and rigorous technical risk evaluation framework, the decision-maker or conceptual designer can obtain a realistic assessment of how likely the technology or concept is to overcome technical and technological obstacles, and achieve the envisioned technological advantages or cost savings over the existing designs and technologies. Technical risk can be evaluated in terms of the likelihood of failing to meet quantitative constraints and requirements concerning technical performance. Accordingly, the assessment technique being developed under this research is based on the evaluation of objective technical metrics, which may also be correlated downstream with level of effort and cost indicators. The research has accomplished the objectives set for its period of performance, specifically: (1) the formulation of the methodological framework for technical risk assessment and of the key steps to be executed in its implementation; (2) the demonstration of the principal

elements of this framework and process, via application to a case study concerning wavefront control for the Space Based Laser (SBL) Program; and (3) the assemblage from commercial building blocks of a simple software tool capable of exercising the case study model. From these basic results, future applications to specific programmatic technical risk assessment needs are believed possible without an excessive level of further development and demonstration effort.

ADAPT: Architecture Design and Performance Tool

R. Clifton and T. Thompson
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The primary objective of this project is to develop an object-oriented replacement for the satellite coverage analysis program called REVISIT. ADAPT will combine a graphical user interface (GUI), a database management system (DBMS), distributed processing, and integrated data visualization with the coverage analysis capabilities found in REVISIT. The work performed in FY98 consisted of developing an object-oriented foundation to support the coverage analysis features. This foundation comprises the persistent data objects required for modeling complex space architectures and storing coverage analysis data, the GUI maintenance screens required to maintain the persistent data objects and control the operation of ADAPT, the distributed processing framework, and the constraint processing framework. Extensive unit-level testing and debugging has been performed throughout the development effort to ensure robustness and throughput.

Integrated Satellite System Architecture Development

A. A. Geiger
National Systems Group

F. C. Cowan, D. Seuss, M. L. Campbell
Computer Systems Division

This project is developing an overarching information system capability for integrating the elements of Intelligence, Surveillance and Reconnaissance (ISR) systems. Previously, we developed advanced architecture concepts to integrate ISR systems in a multi-mission sense. Our current work is focused on detailed planning of a demonstration of an integrated information system.

In the second year of this project begun in mid-FY97, our major accomplishments were: (1) the overall design of the demonstration system, (2) the evaluation of software architectures and associated commercial off-the-shelf (COTS) middleware technologies, and (3) the initial design of two of the software modules (also known as software agents) that make up the demonstration.

The overall design is Web-based, using primarily COTS technology (e.g., using Java as a scripting language) to interact with users and system resources. One of the benefits of this distributed, script-based approach is the de-coupling of ISR workflows from the rest of the system, leading to greater flexibility. The distributed implementation will make it scaleable to thousands of nodes. Several Java-compatible COTS middleware approaches, such as JavaSpaces™ and the Common Object Request Broker Architecture (CORBA), were evaluated.

Architecture Development Center (ADC)

R. Reid, Jr.
Systems Engineering Division

A. Geiger and T. Dunlavey
National Systems Group

As part of a new corporate emphasis on space architecting for civil, commercial and international systems that must interact with national security space systems, IR&D funding is being expended to create an Architecture Development Center (ADC). The purpose of this center is to guide and facilitate the conduct of future space architecting studies within the corporation, and to aid communication with and support for customer architecting studies.

The initial planning stage of this project considers the ADC vision and objectives, an architecting process, analysis tools, an organizational team structure, and support facilities. The ADC vision includes the role of this capability within a hierarchy of architecting problems from the broadest policy and planning levels to the more technically detailed space system and space segment problems. Tools identified and envisioned for ADC usage include existing corporate space system tools and those to be developed for architecture process implementation. A Mission Architecture Process (MAP) has been formulated as a guide and tailorable methodology for architecture studies. Support facilities will include The Aerospace Corporation's Concept Design Center (CDC), to the extent possible, to make economical use of corporate resources.

Smallsat System Analysis and Design

R. C. Gore
Satellite Navigation Department

Classified report on file.

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Recent results from the IR&D program have been published as reports, journal articles and conference papers. They are listed below under each major IR&D research catagory.

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